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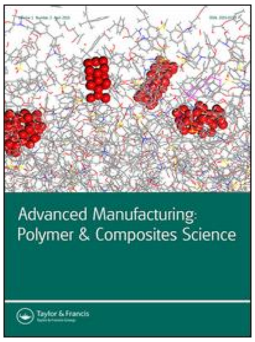

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Strategies for swift automated pick-and-place operations of multiple large-sized layers of reinforcement - a critical review

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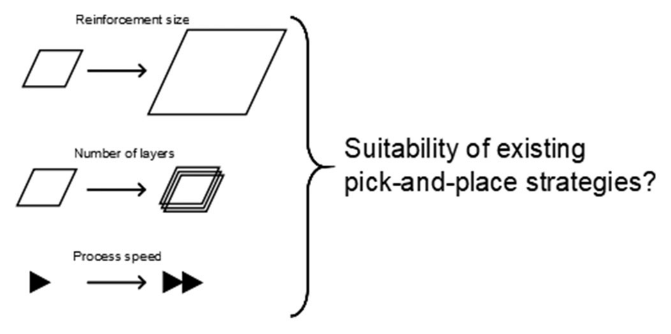
ABSTRACT
For the application of composite materials to become more widespread and replace traditional materials their manufacturing processes and final products will need to be competitive and be e.g. lighter, stronger or stiffer and quicker, easier or more cost-efficient to produce than traditional materials. The state of the art for pick-and-place operations for the manufacturing of composite parts focuses on handling single lab-sized layers at undisclosed speeds. The process could however be more competitive by being able to handle more and larger layers in a faster manner than currently presented in research. The aim of the paper is to evaluate the existing pick-and-place strategies on their suitability for the swift automated handling of multiple large-sized layers of reinforcement. The review shows that many of the existing techniques could be suitable for different scenario's and discusses which factors are to be taken into account when dealing with large layers, more than one layer or rapid handling.



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1. Introduction

The aerospace industry is increasingly replacing traditional materials such as aluminium by Carbon Fibre Reinforced Plastics [CFRPs]. Advantages of CFRPs include their high strength-to-weight ratio and the ability to customize the mechanical properties of the final part. These advantages provide new opportunities in terms of design and weight reduction. Additionally, automated manufacturing of composite parts can reduce their manufacturing costs to below that of a similar aluminium part [1]. Automating the manufacturing process also provides the opportunity for a more consistent and higher quality end product [2]. Existing automated solutions such as Automated Tape Laying [ATL], Automated Fiber Placement [AFP] or dry fiber placement are however not always a suitable alternative for manual lay-up - these techniques are e.g. limited to UD materials and to the handling of strips of material. An alternative to these solutions is an automated "pick-and-place" process where dry or prepreg fabrics that have been (automatically) cut from a roll of material are picked up and placed on a flat layup surface or a curved mould [3,4]. When compared to ATL or AFP, the equipment, tooling and programming required for pick-and-place operations is relatively straightforward and available - making the process competitive even for smaller parts and lower volume productions [1].

Figure 1 illustrates the pick-and-place process. End-effectors are connected to robot arms, which are then programmed to pick, move and place dry

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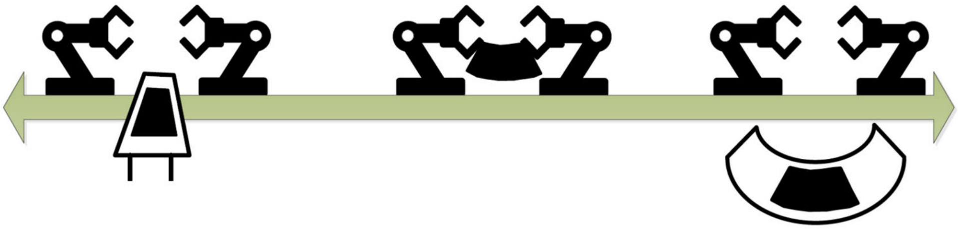

Figure 1. Grip, transfer and drop phases of the pick-and-place process. Adapted with permission from: Schuster *et al.* [5].

or prepreg reinforcements. The pick-and-place process starts as the reinforcement is picked up from the cutting table and is finished once the reinforcement has been placed in or on the mould. Literature shows that there are countless different strategies to execute a pick-and-place operation and that research tends to focus on highly specialized end-effectors, resulting in inflexible single purpose solutions [6]. Björnsson *et al.* [3] and Elkington *et al.* [7] present categories that facilitate discussions on pick-and-place operations by grouping these unique strategies.

Despite a large variety of published research on pick-and-place systems there is not yet a widespread implementation in industry. This can partly be explained by existing technologies being unable to match the ability of skilled laminators when draping fabrics on double curved surfaces or complex moulds [8,9]. A solution for this is the decoupling of lay-up and forming in a two step process [4,9]. An additional advantage of full stack forming is the potentially great reduction in overall draping time and manufacturing cost [7]. The state of the art focuses on the handling of single layers of reinforcement. For this two step lay-up process simultaneous handling of multiple layers is however desirable. A laminate is first stacked on a flat surface, then picked up and formed. In the case of single curved and flat moulds, it could also be possible to pick up full laminates and drape them. These opportunities do require strategies for the simultaneous handling of multiple layers - this could provide advantages in terms of both manufacturing time and cost when compared to handling single layers.

Another factor in the limited implementation in industry is the size of the fabrics handled in literature. Published research generally focuses on lab-sized demonstrators. The maximum ply size reported in literature is $4300 \times 1315\,\mathrm{mm}^2$ [10], with [11] showcasing dimensions up to $6000 \times 1220\,\mathrm{mm}^2$ can also be handled using a similar set-up. These are however not typical dimensions and most demonstrators are designed to handle plies with dimensions smaller than 1000 mm. FRPs are used to manufacture significantly larger parts in both aircrafts and wind turbines. The Boeing 787 does for example have a 60 m wingspan [12] and the current largest carbon/glass hybrid composite wind turbine rotor blade is 107 m long [13]

In order to get the application of pick-and-place processes for the manufacturing of composite materials to the next level, the process needs to be competitive, more reliable and faster than the state of the art processes. This paper focuses on evaluating the current pick-and-place strategies on their suitability for the swift simultaneous handling of multiple layers and on the handling of large-sized layers.

The paper starts by establishing the challenges that are associated with pick-and-place operations of reinforcements in section 2. First, the general challenges will be presented before going into challenges associated with handling large-sized layers or multiple layers. The section will finish by formulating criteria that need to be fulfilled for a pick-and-place operation to be considered successful. In section 3 the different strategies for handling composite plies used in literature will be presented. Hereafter, the strategies are discussed in section 4 using the criteria that have been formulated. Finally, a conclusion is given in section 5

2. Challenges

The end-goal of a pick-and-place operation is to successfully place a reinforcement in or on a mould. Setting requirements for the pick-and-place process and/or the final product will influence how plies are transported from a cutting table to the mould. Different requirements will result in different challenges during automated handling. The interest of the current work lays in challenges associated with the plies. These challenges partly come from the properties of the reinforcement material but also from the ply size and the number of layers that is being handled. Additionally, the quality of the final product is to be in line with the requirements of the aerospace industry. Quality requirements can for example include positional accuracy, accuracy of the fiber directions and requirements for contamination free handling.

Some handling related challenges associated with dry reinforcements are e.g. their low and even anisotropic bending stiffness, sensitivity regarding shear forces, high permeability and structural instability [6,14–16]. Despite pre-preg having more rigidity, shear and bending behaviour are still

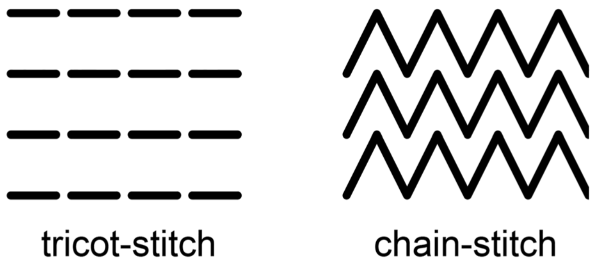

Figure 2. Comparison of chain and tricot stitch type.

important factors to consider when designing the manufacturing process. Pre-preg provides additional challenges through their tack and the backing paper that is present on either one side or both sides of the plies [17].

The non-rigidity of composite plies can result in several problems during the pick-and-place process [18]:

Pick When a reinforcement is picked up the grasping forces can result in deformation of the ply. This can damage the ply and/or result in inaccuracies in the process through e.g. fiber angle variations.

Move The low rigidity of a composite ply can cause high deformations - possibly resulting in unexpected collisions or release during movement. Additionally, depending on the number and location of pick up points a picked up reinforcement can experience high (local) stresses and strains.

Place The deformation of the reinforcement during grasping can make it difficult to achieve an accurate placement. Problems such as edge folding can also occur during the placement operation.

The placement phase of the pick-and-place process typically works by draping the plies in or on a mould. This results in a major limitation of the process with regards to the complexity of mould shapes. Some pick-and-place strategies overcome this limitation by employing a forming principle in the placement stage. However, forming is considered to be typically a separate process to the pick-and-place process. Therefore, the challenges and strategies associated with forming are not discussed.

Fabrics typically found in literature are either unidirectional [UD], woven or Non-Crimp Fabrics [NCF]. Unidirectional fabrics have all fibers parallel while woven fabrics are mostly bidirectional. NCFs are made by stacking unidirectional fabrics in different orientations and stitching them together. An advantage of UDs and NCFs over woven fabrics is that they avoid the crimp found in woven fabrics because the fibers do not cross but lie on top of each other [19]. Compared to woven fabrics NCFs can achieve improved in-plane structural properties due to a reduction in the fiber undulation. Also, UDs and NCFs have more freedom in tailoring the lay-up sequence. However, UDs will have the tendency to split, tear and wrinkle under forming loads due to their low structural rigidity [4,20]. Additional advantages of NCFs include an increase in the lay-up rate due to higher masses per-unit area and a low number of defects due to material handling - even in large cut pieces [21]. An advantage of woven fabrics is however that they typically have better drapability [22]. The drapability of woven fabrics or NCFs is influenced by the knitting/stitching properties or weave type [15,23]. Figure 2 gives two examples of stitches that can be used in an NCF: a tricot stitch and a chain stitch. A tricot stitch will result in a low bending and shear stiffness while a chain stitch will give an NCF with high form stability [24].

Another important factor when looking at the influence of the reinforcement on the pick-and-place process is the size of the reinforcement. The number of points used to pick up the reinforcement should for example depend on the reinforcement size [25]. Increasing the reinforcement size without changing the amount/position of pick up points will result in a larger deformation and larger stresses at the pick-up points. This can not only make the correct placement more difficult but will also result in severe shear deformation, which will have a large influence on the resulting fiber orientations. When extreme deformation is present this could even lead to breaking or tearing of the fabric.

The reinforcements required for the manufacturing of large aerospace components can be too large for a single robot to handle. In those cases multiple robots are required to work together. This can provide challenges in terms of the robot configurations required to pick, move and place the desired cut pieces. Eckardt *et al.* [21] note that they use a geometric link between the two robots to enable them to carry out cooperating movements. In [26] Larsen *et al.* describe their approach to collision-free automatic path planning for cooperating robots.

The pick-and-place process is also influenced by the amount of layers that is picked up. Current research focuses on picking up one layer at a time. Increasing the number of layers handled simultaneously is however a good way to increase the manufacturing output, which can result in a decrease in manufacturing cost.

For the current work layers are defined in two different ways:

Sub-layer A sub-layer is defined as the layers within a NCF. The layers are attached to each other through for example stitches or an adhesive binder.

Layer A layer is defined as a single ply. This can for example be a NCF, woven fabric or UD prepreg.

Increasing the number of sub-layers or layers will affect the pick-and-place process in a variety of ways. For NCFs with sub-layers the behaviour will also depend on the integrity of the binder - whether it is structural or non-structural. Non-structural stitching will consolidate the plies but, unlike structural stitching, it will not form a 3 D reinforcement. In industry several non-structurally stitched NCFs are typically used to make a preform. This whole assembly is then structurally stitched [27]. With a structural binder it will be possible to lift the NCF as a single thick reinforcement. However, when a non-structural binder is used there might, depending on the strength of the binder, be a risk of the sub-layers detaching. When multiple layers or non-structurally bound sub-layers are present the grippers will need to make sure all layers are transported.

The draping process will also be affected by the amount of layers or sub-layers. When an out of plane curvature is applied to a reinforcement there will be a difference in path length between the inner and outer surface. This difference can result in fiber wrinkling. When multiple plies are present each ply will be subjected to this effect. Severe wrinkling will occur if the plies cannot slip over one another [28].

The processability of a stack of multiple plies can be improved by using local stitching - a so-called assembly seam. These stitches facilitate easier handling by locally fixing the layers together. It is undesirable for this assembly seam to influence the mechanical properties of the final product. Therefore, its placement needs to be optimized and its density should be minimized. The deformation behaviour of ply stacks is also affected by the stitches. The local stitching can for example reduce the ability of the plies to shear or transfer shear forces to different areas during forming [29]. Chen *et al.* [30] note that optimizing the stitching pattern to avoid forming defects cannot be done intuitively and therefore used a mathematical algorithm to minimise local shear.

For the case where the intent is to handle multiple large layers of NCF at the same time the pick-and-place strategy is considered to be effective if:

- The pick-and-place strategy does not negatively affect the quality of the ply through e.g. contamination of the surface or permanent distortion of the ply.
- Contact between plies and mould surface and the desired fiber orientations have been achieved within tolerances.
- There are no (sub-)layers left on the cutting table after pick-up or released during movement.

Table 1. Mapping of ply handling methods used in the handling of reinforcements. Based on ply handling methods described by Elkington *et al.* [7].

	Rigid	Kinematic	Compliant	Free ply
Dry	[16,31,32]	[14,15,33–35]	[14,15,33,36,37]	[6,21,38]
Prepreg	[4,22,39–42]	[43–47]	[45]	[4,25,46]
Unspecified	[48]	[49]	–	–

3. Strategies in literature

3.1. Ply handling techniques

Literature presents a wide range of different strategies for the handling of single plies. To aid in discussing the various strategies Table 1 divides them in four categories as defined by Elkington *et al.* [7]. Figure 3 presents schematics for these ply handling methods:

Rigid (A) Plies are picked up using grippers on a rigid frame. This way the ply also becomes rigid during the handling operation. Rigid frames are generally used to move plies from a flat table to a flat mould. Plies are generally picked up straight and placed straight down, e.g. [4,40–42]. Alternatively, pick-up and place down is achieved through a rolling motion [22].

Kinematic (B) Once a ply is picked up a kinematic ply handling system can deform itself to match the shape of the mould. This makes it possible to place plies on more complex shapes. A downside of this system is that the kinematics of the end-effector dictate the complexity of the shape it can conform to. Depending on the system it might only be able to handle a few different features of the mould. Furthermore, when the components to be draped become larger and more complex the number of linkages and actuators required increases rapidly, which might limit further development. The shape of the reinforcement can be matched to the mould while suspended in the air or while placing the ply down. Plies can be picked up straight before being draped in or over the mould [14], but rolling motions are also used [15].

Compliant (C) The compliant ply handling method avoids the above mentioned problems from the kinematic ply handling method by using passive compliant elements that deform as the end-effector holding the ply is lowered onto the mould. Several strategies use a straight pick up before a compliant strategy to drape the ply in or on the mould [14,37] while other strategies both pick up and place down plies through a rolling motion [36,45].

Free Ply (D) Contrary to the previous methods the free ply method does not strictly dictate the shape

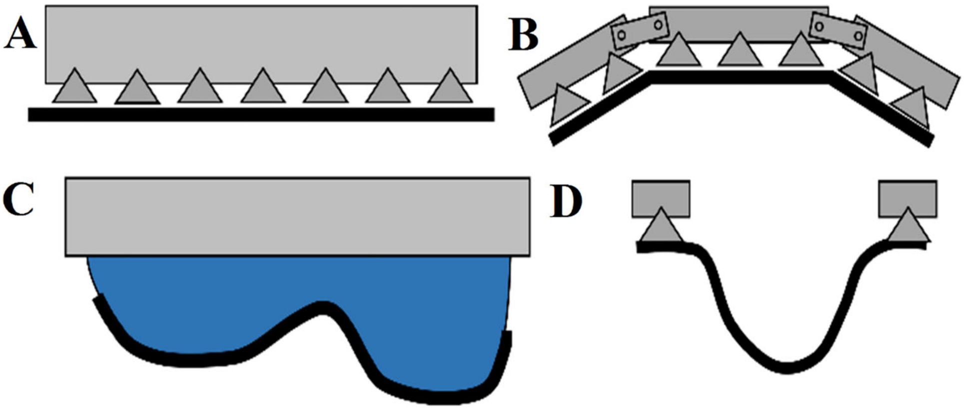

Figure 3. Schematics of four common ply handling methods: (A) Rigid, (B) Kinematic, (C) Compliant and (D) Free Ply. Reprinted with permission from: Elkington *et al.* [7].

of the ply that is held. The plies are generally held at a limited amount of points along corners or edges and left to hang. The sag that results from holding a ply this way has for example been used to dictate where the first contact between ply and mould is and to be able to place plies into a deep convex mould. This way of ply handling is also how plies are generally handled during hand lay-up. A laminator will use their hands to hold a ply and will generally pick them up at opposing edges. The free ply strategy is used for both flat [4,25] and curved [6,21,38,46] surfaces. For curved moulds they can be picked up straight before being actively draped over the mould [21,38,46] while other strategies use an additional roller to place the ply [6]. Björnsson et al. [4] performed some testing on picking up prepreg plies using a peeling motion.

The behaviour of dry reinforcements during handling can be very similar to that of the fabrics used in the garment/textile industry. In addition to pick-and-place operations, this industry also deals with other challenges such as separation, untangling, flattening, (un)folding, hanging and clothing assistance [50]. Despite the garment/textile industry being significantly larger than the composite industry [51] there is not as much development of and variety in the handling strategies; the strategies will typically take a bimanual approach, mimicking a human approach to executing the task. Using the definitions given by Elkington *et al.* [7] these systems would be considered to be using free ply strategies.

To aid in the successful execution of the handling tasks required in the garment/textile industry they use a manipulation technique not found in the handling of reinforcements. This technique is regrasping: during the handling process gripping points are released and placed in a different location. This is for example used to grasp a garment at the desired locations after it has been picked up at a random grasping point [52]. Regrasping in this exact form is not as relevant for the handling of reinforcements due to their relatively delicate nature. It is important that these reinforcements are picked up in the appropriate areas at the start of the handling process to prevent undesired permanent deformations. However, strategic placement and release of pick-up points during the handling process can facilitate accurate placement of reinforcements.

Several strategies have been employed to avoid inaccurate placement of reinforcements. Eckardt *et al.* [21] do for example avoid wrinkles, bridging and distortion by manually teaching their dual arm collaborating robots how to place down the ply. Brecher *et al.* [14] and Kordi *et al.* [33] employ a combination of active and passive draping - as defined by Björnsson *et al.* [3] - to keep the distance between gripping elements constant during fabric manipulation. This process ensures that fabric bridging is avoided and reinforcements can be picked up without introducing displacement or wrinkles. Additionally, Brecher *et al.* [14] note that the electrostatic prototype they present can handle goods without distortion or shifting due to the evenly distributed surface attraction. Buckingham & Newell [25] note that for their set-up in which a free hanging ply is placed down, the initial touch-down point should generally be in the middle of the mould or at a nearby turning point. Doing so allows placement to take place outwards, thereby ensuring that bubbles and wrinkles are continuously moved out of the component. Krogh *et al.* [47] found that the path taken by the grippers during draping has a large influence on the accuracy of the placement of prepreg plies. Wrinkles were easily created with both the uniform draping strategy and the wave shape draping they employed. They conclude that for an accurate placement effort should be taken to determine the optimal trajectories for the grippers. In [53] Krogh *et al.* present an approach to generating these trajectories.

Sensor systems can be used in addition to the above mentioned solutions to control the handling and draping process, e.g. [38,45,46,54,55]. This is for example done by determining suitable placing

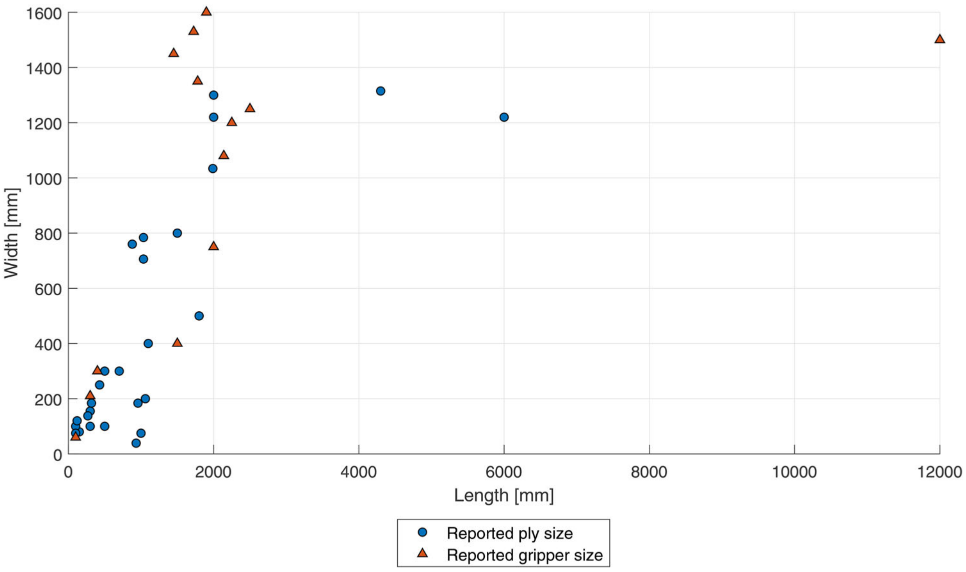

Figure 4. Mapping of ply sizes and end-effector sizes reported in literature.

Table 2. Mapping of grip point distribution. Based on categories defined by Björnsson *et al.* [3].

	Grip points at edges or corners	Grip points spread over surface
Dry	[6,14,21,33,38]	[15,16,31,32,34–37]
Prepreg	[4,22,25,40–42,46]	[39,44,45,47]
Unspecified	–	[43,48,49]

strategies [38], measuring the position and orientation of the ply and refining the location of markers in the fixed world coordinate system [46] or force measurement and camera control [45]. Additionally, several strategies include foam on their end-effector surface to aid with the placement [15,45].

Figure 4 presents an overview of the ply sizes and end-effector sizes reported in literature based on the research mentioned in Table 1. Most studies do not report both the ply size and end-effector size. The data for the graph can be found in Tables A1 and A2 in Appendix A. Figure 4 shows that the largest ply size presented in literature is ± $6000 \times 1200\,\text{mm}^2$, with the majority of plies being smaller than ± $1000 \times 800\,\text{mm}^2$. Grippers are generally used to handle a variety of ply shapes and sizes. The size of the end-effector will need to be chosen such that it can fit the largest ply in the ply book. For the presented end-effectors that are larger than the largest presented ply some authors mention that the dimensions are required for the parts to be handled [16,56] or that the end-effector can be used to grip multiple plies next to each other [36]. For strategies that use a 'Free Ply' handling method the end-effector can be significantly smaller than the plies that are being handled - e.g. the two collaborating end-effectors used by Eckardt *et al.* [21], Gerngross *et al.* [11] and Deden *et al.* [10] are $210 \times 2000\,\text{mm}^2$ while the largest plies they handle are respectively $1989 \times 1034\,\text{mm}^2$, $4300 \times 1315\,\text{mm}^2$ and $6000 \times 1220\,\text{mm}^2$.

3.2. Gripping strategies

All of the above presented ply handling strategies requires a mechanism that connects the ply with the end-effector. Table 2 gives an overview of the positioning of these gripping points in literature. Strategies vary from grabbing the complete surface to only utilizing a minimal amount of pick-up points. Some of the presented strategies are optimized for a specific ply - e.g. [33,40,43,45] - or plybook - e.g. [4,22,39] - while others can be used with a variety of shapes and/or sizes - e.g. [15,16,34,36,37,42]. The optimal placement of pick-up points when handling limp materials using a limited amount of pick-up points has been studied for one-dimensional strips [57,58] and two-dimensional parts [59,60].

There is a wide range of gripping devices that can be used to handle non-rigid materials - see e.g. [61–64]. When reviewing literature on the handling of reinforcements for composite production, five gripping technologies were found to be used:

Needles Needles handle the reinforcements by penetrating the material.

Vacuum Vacuum grippers use pressure or airflow to pick up the material.

Cryo-freezing Cryo-freezing grippers create a contact surface by freezing a previously applied freezing medium.

Electrostatic Electrostatic grippers induce a gripping force by polarizing the fabric.

Gecko inspired Gecko inspired grippers are inspired by their namesake.

Additional gripping strategies used in the garment/textile industry are clamps/pinchers - see [65] for a recent review. Additionally, Lutz *et al.* [63]

Table 3. Mapping of gripping technologies used in the handling of reinforcements.

	Prepreg	Dry	Unspecified
Needles	[40,41]	[14,33]	–
Vacuum	[4,22,25,39,41,42,44–47]	[6,15,16,21,32,34–38,45]	[48,49]
Cryo-freezing	–	[33]	–
Electrostatic	[14]	[14,31]	–
Gecko inspired	–	–	[14]

note that roll grippers can be used to handle textiles and in the past adhesive grippers have been used - e.g. [66,67]. There is an interest in bringing clamping/pinching grippers to the composite manufacturing process: Toggle clamps have been used to handle auxiliary materials [15] and a clamping mechanism has been used in the placement of tapes up to 300 mm in width [68].

Table 3 categorises the technologies used to handle composite reinforcements according to the reinforcement type that is being handled. Each research project is mentioned once. Additionally, there are projects that focus solely on improving gripping technologies to be used with composite reinforcements for: vacuum grippers [54,55,69], Cryo-freezing grippers [64], Electrostatic grippers [56,70,71] and Gecko inspired grippers [71].

The following sections will discuss the different gripping methods and present their advantages and disadvantages.

3.2.1. Needle grippers

Needle grippers can achieve high holding forces [63]. However, the penetration of the material required to pick the reinforcement up using needles can result in damage and displacement of the fibers (e.g. fiber distortion, fiber broadening and buckling [16]), thereby possibly negatively influencing the properties of the finished part [14]. Brinker *et al.* [46] do however note a spring back effect of the textile when pulling out the needles and Buckingham & Newell [25] did not measure a reduction in structural integrity, even when unrealistically large loads were applied. The lay-up precision can however be decreased through the relative motion of the fibers. It is therefore recommended to grip in the excess material [25]. Jarvis *et al.* [32] found that unidirectional fabric in particular tended to slip after initial attachment. Lutz *et al.* [63] remark that additional disadvantages of needle grippers are their high per unit cost and the large installation space that is required.

Seliger *et al.* [64] present the following (theoretical) holding force formula for needle grippers:

$$F_h = \sigma \cdot A_N \cdot n_N = \frac{E_{z6\%} \cdot \delta}{2 \cdot S \cdot \sin \alpha_N} \tag{1}$$

$$A_N = \frac{\delta^2 \cdot \tan \gamma/2}{\sin \alpha_N} \tag{2}$$

where, σ is the surface tension, A_N is the area of a needle penetrating the fabric, n_N is the amount of needles, $E_{z6\%}$ is the Modulus of Elasticity of a Fabric with 6% Extension, δ is the layer thickness, S is the prick distance of the needles, α_N is the penetration angle and γ is the leading edge angle. Figure 5 gives a schematic of a needle gripper.

The minimum holding force required to pick up a reinforcement can be estimated using:

$$\vec{F}_{min} > m(\vec{g} + \vec{a}) \tag{3}$$

where, F is the gripping force, m is the mass of the part, g is the gravitational acceleration and a is an acceleration, which is to be included if it is significant. To pick up the reinforcement F_h will need to be at least equal to F_{min}.

An increase in the number of needles or a decrease in the penetration angle will result in an increase in the holding force of needle grippers. Seliger *et al.* [72] note that the piercing angle should be in the range of $20^\circ - 40^\circ$ for a high holding force. Smaller angles can theoretically result in a larger holding force but can be challenging to achieve. The holding force will be further influenced by properties of the reinforcement such as fiber density, relocatability of fibers and the architecture. A fabric with higher fiber density or a larger amount of crossing points will for example require less needles than one with lower fiber density and a lower amount of crossing points.

3.2.2. Vacuum grippers

The vacuum category includes both low airflow/high pressure difference and high airflow/low pressure difference solutions. The first category includes the traditional vacuum system while in the second the air flow is for example generated by electrical fans or Coanda ejectors. Coanda and Bernoulli grippers both rely on air flow to create a negative pressure that is used to pick up the material but the principles behind the gripper are different. The use of Bernoulli grippers can result in fiber displacement and there is also a risk of deformation when suction grippers are used. Coanda grippers have little risk of leaving marks on the fabric [14,63,73].

Traditional vacuum systems can be categorized in flat and bellow cups. The flat suction cups can generate a faster sufficient holding force due to their low internal volume and are more rigid, which results in better stability and lay-down accuracy in lateral directions. An advantage of bellow suction cups is that they can adapt to uneven surfaces and different laminate thicknesses. Flat suction cups can achieve these advantages by using spring followers

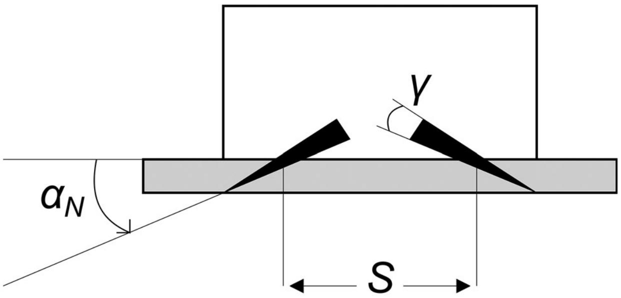

Figure 5. Schematic for needle gripper. Based on Seliger *et al.* [64].

to equal different thicknesses and couplings and ball joints to adapt to uneven surfaces [22,42]. Lutz *et al.* [63] note that suction pads also have the advantage of low unit costs and a small construction space. Additionally, they make it possible to separate plies from a stack and, when compared to Bernoulli grippers, they have the advantage that there is lateral fixation of the plies.

The roughness of the surface to be picked up will influence the ability of vacuum grippers. A higher surface roughness will result in more leakage under the suction cup. To counter this, a higher suction power is needed to enable more effective sealing [25]. The permeability of the fabric results in suction grippers being energetically highly inefficient [14,63,73]. Kühnel *et al.* [42] found that for a more porous fabric pressure charged grippers were better suited while for denser materials vacuum charged grippers is more appropriate. The difference in performance is attributed to the higher flow rate of the pressure charged grippers and the ability to better sustain vacuum of the vacuum charged grippers.

It is possible to calculate the (theoretical) handling force of a vacuum gripper. The (theoretical) holding force formula is as follows [64]:

$$F_h = A_V \cdot \eta(p_0 - p) \tag{4}$$

where, A_V is the area of the vacuum gripper, η is the efficiency, p_0 is the atmospheric pressure and p is the pressure in the gripper. An increase in pressure p will result in a decrease in the holding force F_h. Kühnel *et al.* [42] tested the handling forces of vacuum grippers when picking up PEEK powder impregnated woven fabric. They found handling forces of 0.1 - 0.66 N for vacuum grippers with a vacuum charged effective area and 0.61 - 2.12 N for vacuum grippers with a pressure charged effective area. Brecher *et al.* [14] found a gripping force of ±0.2 N per Bernoulli gripper module.

3.2.3. Cryo-freezing grippers

To pick the fabric up the freezing medium (e.g. water vapors) is frozen using a cooling element, thereby generating a contact surface. Placement of the fabric is achieved by liquifying the frozen vapors using air pressure. With these grippers there is a low risk of damage to the textile, however, [63] the freezing medium brings a contamination risk that can impact the final quality [3,33]. Additional disadvantages noted by Lutz *et al.* [63] are the high cost per unit and a low process stability.

The (theoretical) handling force of a freezing gripper can be calculated using the following formula [64]:

$$F_h = \frac{W_{ad} \cdot A_R}{\delta} = \frac{\sigma \cdot (1 + \cos\theta) A_R}{R_z} \tag{5}$$

where, W_{ad} is the adhesion work, A_R is the area of the freezing gripper, δ is the layer thickness, σ is the surface tension and R_z is the surface roughness. Seliger *et al.* [64] note that they realized holding forces of up to 40 N when handling carbon fiber preforms.

The cryo-freezing gripper is a strategy relying on an adhesive gripper principle. Adhesion between gripper and fabric can also be obtained using other media. Dutta & Schmidt-Eisenlohr [74] do for example present a patent for the adhesive handling of semi-finished fiber products using matrix material.

3.2.4. Electrostatic grippers

An electrical field is created by applying different potentials to the gripper electrode [14]. The material is released by turning the voltage off or by leaving the material at an area with a higher electrostatic attraction. The release through turning the voltage off can be aided by an airstream coming from the gripper [73]. Electrostatic grippers allow the air-permeable reinforcements to be handled reliably and damage-free [14]. Advantages of electrostatic grippers over vacuum grippers when handling fabric plies include their light weight, an uniform surface force, ease of re-configuration, simple construction and low cost [70]. Jarvis *et al.* [32] do however decide against using electrostatic gripping because they believe high electrical potentials are undesirable in an environment where a lot of highly conductive carbon strands and dust can be found.

Under the assumption of a uniform field the holding force applied to a ply by a single-pole electrostatic gripper can be calculated as [56]:

$$F_h = A_E \cdot \varepsilon_1 \left(\frac{V}{d_1}\right) \tag{6}$$

where, A_E is the area of the electrostatic gripper, ε_1 is the permittivity of the insulation layer of the electrostatic gripper, V is the voltage and d_1 is the thickness of the insulation layer. The electrostatic pad presented by Ruffatto III *et al.* [75] can support up to 112 N in shear on a glass substrate.

3.2.5. Gecko inspired grippers

Gecko grippers are inspired by the mechanisms that aid the gecko in climbing walls and hanging upside down - van der Waals interactions enabled by the tiny hairs on their toes [76].

Dadkhah *et al.* [71] mimic the gecko gripping technology by using $20\,\mu m$ x $60\,\mu m$ triangular wedges. This results in a directional dry adhesive. Applying a shear force in the correct direction will result in the adhesive force being turned on, reversing the load will result in a release. The authors combine this adhesive with an electrostatic gripper and show that the addition of electroadhesion improves the handling force.

Brecher *et al.* [14] generate van der Waals forces by rolling the polymer sheet out on the ply to be picked up. To release the ply this process is executed in reverse. Advantages of this technology include the ability to handle most surface types and not being dependent on a power supply. However, the authors note that flexible goods risk being rolled in with the polymer sheet upon release and that the gripper is vulnerable to contamination. This technology can therefore not compete with gripper systems such as vacuum or needle grippers [14].

4. Discussion - Handling multiple large-sized layers

Literature has shown that there is a wide range of strategies that can be used to handle reinforcements for composite production. These strategies consist of a combination between a ply handling method with a certain amount of gripping points. These gripping points can use a variety of gripping technologies. The different strategies are evaluated based on whether they can swiftly handle multiple large-sized layers while:

- Not negatively affecting the quality of the ply through e.g. contamination of the surface of permanent distortion of the ply,
- Ensuring that after draping plies are fully in contact with the mould and the desired fiber orientations have been reached,
- Making sure there are no layers left on the cutting table after pick-up or any layers released during the pick-and-place process.

4.1. Ply handling strategies

The majority of ply handling strategies presented in literature is limited in the complexity and diversity of geometries they are able to handle. A wide variety of strategies can be used for the placement of plies on flat surfaces or single curved moulds. More complex moulds will however often become challenging for most strategies. Rigid ply handling strategies are the most limited in their possible placements but kinematic ply handling strategies and compliant ply handling strategies will also both typically be limited to use with a single mould.

Some compliant ply handling strategies can handle complex and diverse mould surfaces. Examples of a compliant ply handling strategy achieving complex placements are the system presented by Ehinger & Reinhart [36] and the FormHand technology presented by Löchte *et al.* [37]. These systems are able to conform to challenging moulds thanks to their form-flexible end-effectors. The system is not limited to a single mould and can adapt itself to different mould surfaces.

An alternative strategy is a free ply strategy with (a) consolidation roller(s), as presented by Flixeder *et al.* [6] for strips of fabric. Cooperation between the pick-up points and the roller(s) ensures that the ply is gradually placed in/on the mould while the roller(s) ensure(s) proper contact - thereby mimicking the work of a laminator.

Of these two strategies, the compliant based systems are the most practical as long as you're handling single plies with limited dimensions. The compliant based systems will be able to adapt to any mould without extensive programming and will also have a higher lay-up rate. However, the dimensions of the end-effector will need to be at least equal to the dimensions of the ply to be handled. When dealing with large plies this can result in end-effectors with e.g. impractical dimensions, impractical weight or insufficient stiffness. Additionally, since the technique used with these systems is a vacuum-based technique, it will not be possible to lift multiple layers.

There is a wide variety of applications where moulds are not complex. Depending on the exact mould typically either kinematic, compliant or free ply handling strategies can be used. However, as discussed previously, with an increasing ply size the free ply strategy becomes more interesting. On the other hand, if more control over the ply is desired, a kinematic or compliant strategy with more pick-up points should be chosen. Adding a compliant element to a predominantly kinematic ply handling strategy - as for example used by Brecher *et al.* [14] and Kordi *et al.* [33] - can be used to improve the accuracy of the placement. Using a strategic release and placement of pick-up points inspired by the regrasping technique seen in the garment/textile industry can be used to facilitate accurate placement.

An alternative ply handling strategy is placing a minimal amount of pick-up points along the edges of the reinforcement and applying a pre-tension to aid in handling of the material. Applying a pre-tension ensures the reinforcement(s) can be handled without experiencing deflection while using a limited amount of gripping points. With this approach care is to be taken that the tension is applied in the directions of the fibers. A misalignment between the fiber direction and the direction of the pre-tension will result in a force being applied in a direction with low resistance to deformation - resulting in undesired deformation. When multiple fibre directions are present - as with a woven fabric or NCF - care needs to be taken that the pre-tension is applied in such a way that all fibre directions are taken into account.

When the speed, accelerations and decelerations of handling during a pick-and-place operation are increased a strategy with more control over the ply area will have a lower risk of movement induced distortions. A free ply strategy is the least appropriate strategy for handling at high speeds since there is a large chance of ply distortion. A rigid ply handling strategy or a compliant strategy with full control over the surface will avoid movement induced distortions of the ply. A kinematic or general compliant strategy with strategically placed pick-up points can be a good compromise between a free ply and a rigid strategy.

4.2. Gripping strategies

Since most gripping principles have a chance of damaging the material they are handling it is preferable to place gripping points in the excess material as much as possible. If this is not possible because this results in excessive displacements, deflections or strains gripping points in the ply should be considered. Increasing the amount of pick-up points will reduce these stresses but will result in more complex strain patterns. In a scenario where pick-up points in both the excess material and in the ply are required it can be worthwhile to use a combination of different gripping strategies. For the excess material needle grippers, with their possibility for high holding forces but also a risk of deformation to the material, could be used. For the ply area an alternative strategy such as electrostatic grippers or coanda grippers is preferred

Gripping points restrict the areas they are in contact with. A limited amount of strategies is designed such that these areas can deform after gripping (e.g. [14,36,37]) but for most strategies these gripping areas will be rigid. The restricted area differs per gripping strategy: a vacuum gripper will for example typically restrict a larger area than a needle gripper. A gripping strategy with a larger gripping area will affect the potential deformation of the ply. This will affect the accuracy of the placement when curved moulds are used. The gripping strategy should therefore also be matched to the mould. For a mould with (relatively) small curvatures a gripping strategy with a smaller gripping area, such as needle grippers, will be more favorable.

Increasing the size of the ply does not have to affect the choice of gripping strategy but it does affect the amount and placement of the points. With an increase in ply size it becomes more important to avoid an oversized gripping system that has an unnecessary large weight and energy consumption.

For the handling of multiple layers some gripping principles are more suitable than others. The most suitable type of gripping is the use of needles. By using needles it is possible to pierce and secure multiple layers. The maximum thickness of the reinforcement stack will depend on the maximum stroke of the needles. By setting an adjustable stroke to the desired dimension, as is for example possible with [77], it is also possible to pick up a predefined number of layers [63].

Vacuum grippers are not suitable for handling multiple layers. When low permeability layers are used there will be no airflow reaching the lower layers, making it impossible to handle more than one layer. For layers with a high permeability there will be a large amount of losses, which results in the process being energetically highly inefficient. The cryo-freezing, electrostatic and gecko inspired strategies will also not be appropriate: When multiple plies are present these strategies will only be able to pick up the top layer, while the other layers will remain on the cutting table.

The pinching and clamping strategies used in the textile industry are able to handle multiple layers. For scenarios where the handling of multiple layers is desired it would be interesting to further explore the possibilities these gripping strategies could bring. Disadvantages of clamping grippers include that they typically require access to both sides of the fabric and need to be able to approach the edges. Pinchers, while very effective in picking fabrics, will

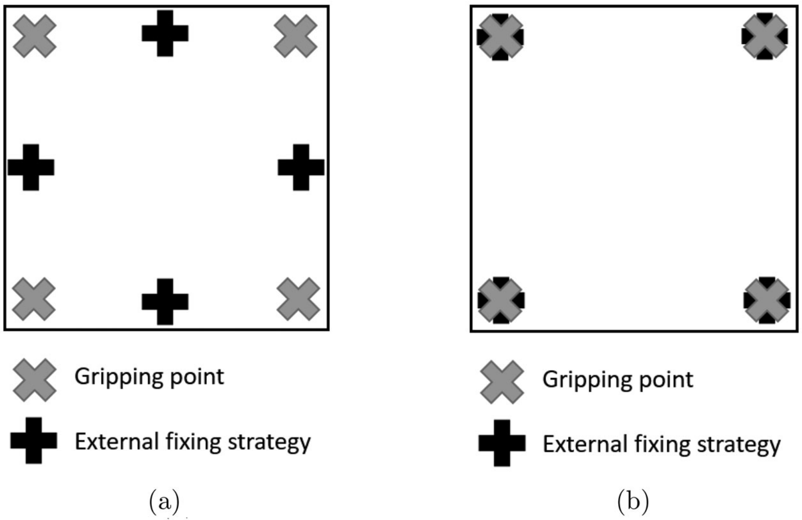

Figure 6. Placement of gripping points and external fixing mechanisms. (a) Separate gripping and fixing areas. (b) Coinciding gripping and fixing areas.

experience difficulty placing fabric without folds or wrinkles. [61].

An alternative strategy to handling multiple layers is to decouple the gripping strategy and the mechanism holding the plies together. This can for example be done using assembly stitches. These stitches will influence the local shearing behaviour and should therefore either be placed in the excess material or very carefully placed in the correct area. Some solutions that can be used in the excess material to facilitate handling can include placing eyelets/grommets or using the inherent ability of the material to become one through local melting and/or curing - similar to spot welding. Figure 6 illustrates that these 'external fixing mechanisms' can either be placed in a way that they are separate from the gripping points (Figure 6(a)) or such that the fixed areas correspond with the gripping points (Figure 6(b)).

The addition of these areas in which the multiple layers are locally fixed does not result in all gripping technologies being suitable. If these fixed areas do not correspond with the gripper areas - see Figure 6(a) - the issues discussed above will still mostly be present. It might be possible to lift the stack of plies, but with the top layer being the only one connected to the pick-up points it will not be possible to control the placement. The top layer will also experience large stresses and strains since the rest of the stack will only start to lift after the distance between the pick-up points and fixed areas has tightened.

Alternatively, the pick-up points and fixed areas are designed to coincide - see Figure 6(b). If stitches are applied such that they provide an area for the gripping mechanism to grab they do overcome the issues associated with plies being left on the table. The same can be said for a fixing strategy that is based on local melting/curing of the reinforcements. While eyelets/grommets bring advantages for the handling of multiple layers by distributing the stresses and locally stiffening the stack their placement will hinder the use of most techniques. Since eyelets/grommets remove part of the reinforcement the surface area that can be gripped is greatly reduced. They do however bring possibilities of e.g. using clamping/pinching techniques to pick up the stack at the eyelets/grommets.

Any strategy that fixes the movement of plies that are handled together can cause issues when dealing with a curved mould. The differences in path length between the inner and outer layers, combined with the plies not being able to slip over one another result in severe wrinkling. Potter *et al.* [28] note that this would be considered to be a process induced defect. Unlike a design related defect/feature which might not be acceptable but can only be avoided/changed at the design stage a process induced defect can be avoided by changing the manufacturing process [28]. Simultaneously draping multiple layers is therefore not a suitable strategy for every mould surface. Depending on the design these drawbacks can possibly be circumvented through careful and strategic release of part of the pick-up points during the draping process. A different solution is to use a two-step process where the layers are transported using a pick-and-place process before being formed.

The risk of layers releasing during the pick-and-place process will be larger when the speed, accelerations and/or decelerations are increased due to the additional forces. The different gripping technologies will be affected differently by these additional forces. Needle grippers will be less susceptible to releasing layers due to their gripping mechanism that physically holds all layers. Vacuum grippers have difficulty handling multiple layers, the first layer will always be held more rigidly than the following layers. When speed, accelerations and/or decelerations are increased vacuum grippers will need to exert an even larger amount of suction to hold the layers. The other gripping methods - cryo-freezing, electrostatic and gecko-inspired are unable to handle multiple layers without external fixing mechanism. The external fixing mechanisms as described above will prevent part of the stack from detaching. However, the holding forces will still need to be increased to prevent the complete stack from falling.

5. Conclusions

A wide variety of strategies is available for the handling of reinforcements. However, if the intent is to swiftly handle large layers and/or multiple layers part of these strategies will no longer be suitable. Conclusions can be summarised as follows:

1. The best way to ensure the quality of plies is not affected by the pick-and-place operation is to grip in the excess material. Increasing the amount of pick-up points is not necessarily the best solution to decreasing the chance of damage to the plies - while the stress/strain will decrease, the stress and strain patterns will also become more complex. The optimal amount and location of pick-up points depends on quality and cost requirements and requires further research.
2. All four ply handling methods can be suitable for the simultaneous handling of large-sized layers of reinforcement. The choice made in ply handling method will depend on e.g. the mould and reinforcement used in the manufacturing operation. As ply size increases it does become more interesting to go more towards a free hanging strategy.
3. An alternative solution to handling reinforcements while using a limited amount of pick-up points is to place gripping points along the edges and to apply a pretension to ensure no (excessive) deflection is experienced. If this strategy is used care should be taken to ensure the tension is applied in the fiber directions to avoid undesired deformations.
4. When multiple layers are concerned needle grippers are the only gripping principle typically used for the handling of reinforcements that is able to lift all plies without an external fixing mechanism. The clamping strategies found in the textile/garment are also able to handle multiple layers. Additional fixing strategies can be used to facilitate handling using other gripping mechanisms. When fixing strategies are used the fixed area should coincide with the gripping area. The limits of handling multiple layers - both in terms of amount of layers and mould complexity - are currently unknown, research is required to study these limits.
5. The speed, accelerations and decelerations of the pick-and-place process will affect the process through the introduction of additional forces. As these parameters are increased it becomes more desirable to fix the ply - as opposed to free hanging. The additional forces resulting from an increase in speed, acceleration or deceleration mean a larger handling force is required. Additional research is required to quantify the effect of increasing the speed, accelerations and decelerations in pick-and-place processes on strategy choices.

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Appendix A

Table A1. Dimensions of plies presented in literature.

Source	Length [mm]	Width [mm]
[33]	1060 to 1500	200 to 800
[4]	300 to 430	155 to 250
	150 to 700	80 to 300
	500 to 1100	300 to 400
[46]	880	760
[22]	300	100
[38]	500	100 to 1800
[54]	100	100
[5]	100 to 1000	75
[56]	120	120
[21]	1989	1034
	1034	706 to 784
	268 to 318	139 to 184
	933 to 958	139 to 184
[11]	6000	1220
	2000	1220
	2000	1300
[10]	4300	1315

Table A2. Dimensions of end-effectors presented in literature.

Source	Length [mm]	Width [mm]
[37]	300	210
[32]	2000	750
[35]	12000	1500
[16]	2250	1200
[21]	2000	210
[36]	2140	1080
[15]	1450	1450
	1900	1600
	1780	1350
[69]	100	60
[49]	1500	400
[48]	1725	1530
[56]	2500	1250