STRATEGIES FOR THE MANUFACTURING OF WRINKLE-FREE COMPOSITE PARTS

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ABSTRACT

Out-of-plane fiber waviness, also referred to as wrinkling, is considered one of the most significant effects that occur in composite materials. It significantly affects mechanical properties, such as stiffness, strength and fatigue and, therefore, dramatically reduces the load carrying capacity of the material. Fiber waviness is inherent to various manufacturing processes of fiber-reinforced composite parts. They cannot be completely avoided and thus have to be tolerated and considered as an integral part of the structure. Because of this influenceable but in many cases unavoidable nature of fiber waviness, it might be more appropriate to consider fiber waviness as effects or features rather than defects. Hence, it is important to understand the impact of different process parameters on the formation of fiber waviness in order to reduce or, in the best case, completely avoid them as early as possible in the product and process development phases. Mostly depending on the chosen geometry of the part and the specific manufacturing process used, different types of fiber waviness result. In this study various types of waviness are investigated and a classification scheme is developed for categorization purposes. Numerous mechanisms of wrinkling were analyzed, leading to several recommendations to prevent wrinkle formation not only during composite processing, but also at an earlier design stage, where generally several influence factors are defined.

1. INTRODUCTION

Fiber-reinforced composite materials allow for a significant reduction in weight due to the comparably low density (c.f. 4-5 times less than steel) and, in addition, fibers can be aligned in accordance with the load paths. This possibility of alignment allows the fibers to be placed at the exact position where they are needed to provide the component with the required stiffness and strength. However, this can lead to a load path-optimized composite structure, which is not necessarily producible easily and defect-free. The placement of the fibers or semi-finished textile products is still often carried out by hand, especially in the aviation industry. This allows a diverse draping of the unidirectional (UD) layers, woven textiles or non-crimped fabrics (NCF) into the production tool. However, manufacturing effects such as fiber waviness, porosity, delamination and distortion cannot be completely avoided. The increased demand for composite parts for the aviation and automotive industries requires a transition to (partially) automated manufacturing processes. Those systems come with a higher deposition rate and ensure reproducible quality, but also imply production effects, e.g. fiber waviness [1,2]. This necessitates a well-founded understanding of those implicit effects on the mechanical properties of the manufactured structure. The decision as to whether these unwanted irregularities are considered as manufacturing features (effects), or as defects, depends on the size, number and location of the effects in the component. This limit criterion depends on the strength and stiffness reserve at the location of the feature, as well as on functional requirements, e.g. water tightness. The assessment of manufacturing effects further depends on the industry. In the aviation industry, the allowance limits for defects are very restricted, while in the automotive industry the need for short cycle times leads to a trade-off between robust processes and tolerated manufacturing imperfections. To this point, there is still no generally accepted approach to quantitatively support accept/reject/repair-decisions and make a consistent assessment of wavy layers in composites. If the effect is termed to be a defect, typically a deviation from design must be requested in the aviation industry and an individual decision must be made on "use as is", repair or reject entirely. In some cases experiments on representative test samples are performed at the subcomponent-level on a statistical basis. However, this is both time consuming and cost intensive. It is necessary to strive for a fiber-oriented and in particular a manufacturing-oriented design and construction of composite components. Towards this goal, design and production engineers aim to expand the permissible margin of safety by assessing the effect on stiffness and strength of those production effects, i.e. fiber waviness, porosity, delamination etc. Additionally, they aim to reduce or, in the best case, avoid them on the process side, increasingly with the help of finite element based process simulations.

2. DEFINITION OF TERMS

There is no universally accepted terminology and consistent use for the differentiation between waves, wrinkles, folds, marcels, undulations and misalignments (Figure 1). Definitions of these terms are given below for the sake of clarity. Ply/Fiber **waviness or wrinkling** is a commonly observed manufacturing effect in composite parts resulting in decreased mechanical performances. Fiber waviness is denoted as a wave-formed ply and/or fiber deviation from a straight alignment in a unidirectional laminate. This may arise as an undesirable manufacturing effect that commonly occurs during draping, infiltration and/or consolidation/curing process steps. Sometimes these waves are also referred to as **marcels**. If the out-of-plane fiber waviness occurs due to stability issues when the ply is loaded under compression, it is also referred to as **buckles or fiber buckling**.

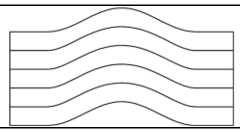
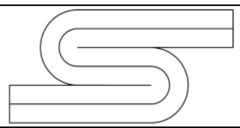
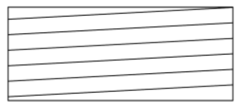
Wave/Wrinkle	Fold	Undulation	Misalignment
			

Figure 1: General definition of deviations from the intended fiber orientation, i.e. wave/wrinkle, fold, undulation and misalignment.

Wavy plies can appear in arbitrary shapes and locations and can principally be classified into in-plane and out-of-plane waves, whereas Nelson et al. [3] stated, that both show similar strength degradations. This paper aims to investigate out-of-plane waviness because of its more frequent occurrence compared to in-plane waviness. In this work, **folds** are considered as a special type of waviness with a maximum deviation of the fiber misalignment where a layer comes into contact with itself. **Undulations** are considered to be small-sized fiber misalignments at the mesoscopic level in the form of waves inherent to various preform manufacturing processes, such as woven textiles where fibers are undulated between warp and weft directions. **Fiber misalignment** is the general description for the angular deviation of nominal, intended fiber directions and therefore not corresponding to the designed load path. Misaligned fibers remain straight compared to curved fibers in waves, wrinkles or undulations. Nevertheless, in many publications the term fiber misalignment is used as an umbrella term including waves, wrinkles and undulations.

3. OCCURRENCE OF FIBER WAVINESS

The origins of fiber waviness are manifold and can be caused by several factors. These effects can occur in manual hand lay-up processes, which are strongly influenced by the skills of the operators, and also in highly automated production processes. Any composite manufacturing process is associated with a number of specific effects. The classification of waviness-inducing effects serves as an overview of the numerous origins and influence factors on the formation of out-of-plane fiber waviness and provides a general guideline on how to reduce and, in the best case, even avoid the occurrence of wavy layers at an early stage of product and process development.

3.1 Mechanical loading and coupling effects

3.1.1 Coupling effects according to classical laminate theory

The deformation behavior of fiber reinforced plastics is very different from that of isotropic materials. With isotropic materials, normal stresses only cause normal strains and shear stresses only shear strains. Within fiber reinforced plastics, this decoupling is only possible under certain conditions. In the most general case all elements of the [ABD] matrix [4], which relates cross-sectional forces and moments to mid-plane strains and curvatures, are occupied. If symmetries are introduced in the stacking sequence of the laminate, some elements result to zero. Especially in forming/draping steps layers exhibit varying loads which can lead to a complex internal stress state. These can in turn lead to wrinkling mostly due to non-zero elements in the B matrix. Depending on boundary conditions, such as orientations of neighboring layers or compaction forces, these loads can lead to severe out-of-plane deformations. An example of this mechanism can be observed, for example, in off-axis tensile tests of unidirectional prepregs leading to pronounced out-of-plane wrinkling.

3.1.2 Mechanical deformation of layers due to manual handling of preforms, moving sliders and closing tools

Fiber misalignment in general, and fiber waviness specifically, often originate from the labor-intensive preform placement into the mold cavity prior to infiltration and curing steps. The quality of draping is therefore strongly dependent on the skill and experience of the operator. Fiber waviness may be also formed due to mold closure effects when the fiber preform is compressed during mold closing, inducing tension forces around curvatures and bends, particularly in massive, geometrically-complex parts or when sliders move the plies away from its intentional position [5,6]. [7] stated that fiber waviness can also occur when slightly oversized preforms are forced to fit into a mold cavity. This is not considered to be a manufacturing effect but more a design issue, as this problem can be solved by adapting the size of the ply.

3.2 Path length differences

3.2.1 Micro/meso scale deformation at the material level

Bended continuous fiber-reinforcements tends to form out-of-plane waviness as a result of path length differences between the upper and lower side of the ply [1]. This effect is considered to be caused at the material level. When forming a multiple-ply stack, each ply is exposed to these path length differences. In addition to that, waviness can occur if the ability of the plies to slip between each other is too low or even restricted. This effect can be controlled by the forming rate, temperature control and the distance of the point of forming to the free edge where the necessary slip between the plies must be accommodated [1].

The thickness of a typical layer is much smaller than the width, and therefore the bending stiffness out-of-plane is much smaller than in-plane, consequently out-of-plane is the predominantly occurring case of waviness. [8] state, that thermoset pregregs are more prone to fiber buckling in form of wavy layers because of their lower bending stiffness compared to layers used for liquid composite molding processes which are usually thicker.

3.2.2 Global deformation on structural level at double curved and joggled geometries

When a material, regardless of whether it is dry or pre-impregnated, is draped around a double curved surface, e.g. hemispheres [1,9] or joggled geometries [10,11], the path length difference of the reinforcement and the path on the geometry to which the material must map on the surface can vary significantly, thus leading to a pronounced risk of wrinkling of the layers due to path length differences at the structural level. The complexity of the final part tremendously influences the occurrence of fiber waviness. Potter et al. [1] stated that only a slight difference in path length can lead to obvious fiber waviness. Furthermore, the probability of fiber waviness is strongly dependent on the pathway, as there are generally several ways by which the draping can be achieved [12]. Especially the placement of fiber reinforcements by hand allows for a very diverse draping into the production tool, but the occurrence of fiber waviness cannot be completely avoided. Depending on the pathway, higher or lesser skills of the operators are required to achieve a defect free part. The effect of differences in the path length strongly depends on the choice of material and the geometry design. Regions of double curvatures involve membrane stretching stresses and shearing stresses. Thus, the buckling force is mainly composed of two components, i.e. the membrane stresses and the loading force due to holding pressure. During the deformation of the material, the curvature and the stresses generated in the material change. These are, according to Lin et al. [13], functions of time, temperature, processing rate and holding force. Wrinkling may occur by buckling of the tows along the circumference of the hemisphere if the compressive force exceeds the critical buckling force. Lin et al. [13] also reported that the dominant mechanism in global deformation during textile composite forming is out-of-plane bending (shell-type curvature). Several experimental studies [14,15] have reported that, amongst other factors, stress conditions induced by manufacturing boundary conditions, deforming rates, original blank dimensions and strain gradients play a role in their development. Boisse et al. [9] have also shown that the formation of out-of-plane wrinkles is a global phenomenon dependent on process conditions, e.g. blank-holder pressure, and all types of strains and rigidities of the composite material. Low forming speeds also reduce the possibility of wrinkling by generating lower resistance to inter-ply and intra-ply shearing, thus allowing the blank to deform more easily [16,17]. Generally, when the draped reinforcement arrives at a flat region, the distortions in the tows needed to accommodate the curvature continue across the flat regions [1]. The tendency of wrinkling, occurring from a so-called drape run-out, is significantly reduced if the layers to be formed have a shape and size which results in as little excess material as possible at the edges [18]. Additionally, these wrinkles can be, at least partially, avoided by higher consolidation pressure during autoclave curing or blank holder forces to keep the plies under slight tension during molding in forming processes. The type of holding fixture and the position of springs is usually determined by prior experience and considerable trial and error or, increasingly, with the help of process simulations. The blank holder may induce tensile stresses by spring elements or vertical clamping rings used to keep the flange flat. For parts with significant double curvature and requiring the use of a large area draped reinforcement layer, the selection of a woven fabric with a narrow rather than a wide tow reduces the level of fiber waviness [5]. By including these influencing factors in the design decisions, this effect can be reduced.

3.2.3 Steering

In automated fiber placement (AFP) [19], a fully automated manufacturing process for ribs or flat composite components, robot-guided fiber-reinforced prepreg tows are placed along a predetermined path on the three-dimensional tool surface using pressure and temperature. Due to the path steering of the head, the layers can be ideally orientated according to the load path. However, different defects such as bridging, gaps between the deposited tapes, in-plane or in the further out-of-plane buckling of the tape or a lifting of the tape on the outside of the tape as the radius narrows, may occur. The formation of these defects is overall a function of the steering radius chosen in the design process. During steering, the tape is bent in the plane of the surface, which causes the fibers along the inner edge to be under compression and the outer slit-tape edge to be under tension [20]. The inner edge of a tape placed along a curved trajectory tends to buckle in the form of localized out-of-plane waviness when the radius reaches a specific limit. This limit depends on parameters such as tape width and thickness, material, temperature control, etc. The tape pull-off [20,21] is caused by the tension state at the outer edge of the steered tape. The mechanical behavior of the fiber mainly determines the resulting cylindrical deformation mode. The fiber can be assumed to be almost inextensible, causing high tensile stresses. In combination with an insufficient prepreg tack, the tape starts to fold at the outer edge. In-plane fiber waviness and out-of-plane tape buckling are two effects that are assumed to occur subsequently [21]. A careful control and selection of process parameters (i.e. heating temperature, compaction pressure, deposition rate), machine trajectories (i.e. steering radius), together with material parameters (i.e. tackiness and tow width), is of crucial importance for obtaining a high quality, defect-free laminate. Sensitivity studies by Beakou et al. [22] have shown that the prepreg tack and the tow width strongly affect the critical buckling load. However, care must be taken to avoid stretching of the outer fiber of the tow to prevent lateral compressive stresses leading to a transverse buckling phenomenon. Lower compaction forces lead to placement without tow wrinkling, however a minimum force must exist to ensure tack. For productivity reasons, manufacturers strive for high deposition rates. However, it was observed by Beakou et al. [22], that high deposition rates promote the occurrence of tow wrinkling. Depending on processing parameters, tow wrinkling may also recover many hours after fiber deposition.

3.2.4 Consolidation in corner areas, external radii, stepped or tapered laminates

The autoclave consolidation of thick laminates in inner corner geometries can force the plies to move in the corner direction and form wrinkles due to the pressure acting at the end of the layup. This effect depends on the length of the laminate arm (limb length) as it influences the possibility of ply slippage and, therefore, can be addressed in design decisions and manufacturing planning. In vee bending [23], the compressed fibers in the bend region can lead to wrinkling provided the compressive stresses exceed a certain limit. In contrast, Potter et al. [1] state that even a small amount of consolidation of the plies over an external corner can lead to an excess length that must be accommodated by the forming of wrinkles if no slippage can occur. The debulking of the plies over an external radius during the consolidation process ensures a correct fit on the tool geometry and improve adhesion between the layers. The outermost plies are forced into a tighter geometry, leading to an excess length. If layers can shear/slip over one another, the additional length can be accommodated by producing so-called “bookends” [8]. However, if the tack between the plies is too high, axial compressive stresses are built up in the layers which may form wrinkles. The size of radius plays an important role, especially in internal corners. It becomes more difficult to place the prepregs accurately into internal corners with decreasing radius. The quality of the layup strongly depends on the size of radius, the ply thickness and the final laminate thickness. Larger corner radii are less likely to be bridged and, according to [5], will definitely have lower levels of fiber waviness induced by the curvature of the prepreg. The bulk factor β, which describes the ratio of the initial laminate thickness t_i to the final thickness t_f of the fully impregnated part after curing, is an inherent characteristic of the material. Materials with high bulk factors, e.g. out-of-autoclave semipregs, are more prone to wrinkling compared to low bulk factor plies, e.g. traditional prepregs. To improve the laminate quality and reduce the risk of fiber waviness, pre-consolidation every 4-5 layers using a vacuum bag is recommended. This is especially important for reinforcements with high bulk factors. However, Lightfoot et al. [24] reported that frequently conducted debulks during hand lay-up had no influence on the wrinkle formation compared to non-intermediate debulks.

3.3 Non-uniform pressure distribution

3.3.1 Co-bonding (or pre-cured parts in LCM process)

Large stiffened composite panels used in aircraft are often produced in a co-bonding process, i.e. pre-cured stiffeners are co-bonded to the wet skins and webs in an autoclave process. The co-bonding allows for an integral design that reduces or even eliminates drilled holes and mechanical fasteners. This, in turn, reduces complexity, weight, material and tooling costs etc. However, co-bonding may also lead to undesirable effects such as fiber waviness, voids, adhesive pockets and resin pockets. These effects typically occur at the stiffener edges. [25] Rubber pads can be used to achieve better pressure distribution [26,27]. Similarly, rubber-die molding processes [18], which are closely related to matched-die molding but at significantly cheaper mold costs, may reduce the risk of wrinkles in the part through more evenly applied pressure.

3.3.2 Telegraphing effect of face sheets at honeycomb core

The telegraphing effect [28] is a result of the integral building technique of sandwich structures. In production, the face sheets are placed directly on the honeycomb core in a wet lay-up process. The sandwich structure is then cured in the autoclave at elevated pressure. The use of large cell size honeycomb cores in sandwich structures in combination with thin skins may result in telegraphing effects, which are characterized by a dimpled outer surface. These dimples are treated as small-sized waviness. A smaller cell size also improves the surface appearance and bonding quality due to its larger bonding area, but also increases its weight and cost. Secondary-bonded face sheets can almost completely eliminate telegraphing [29]. Riss et al. [30] developed an anti-telegraphing solution with additive layer manufactured honeycombs.

3.3.3 Welding spots

During spot welding of thermoplastic laminate stacks, indentations in form of wavy layers can occur due to the local elevated contact pressure of the welding horn and resulting softening material behavior caused by increased temperatures. These ply stacks are mostly positioned by the welding spots and further processed in a forming step. Fischer et al. [31] reported that after consolidation, the imprints remain distinct atop the compacted sample, and the previously disrupted fibers are clearly recognizable. If possible, these welding spots may be positioned in non-critical areas of the part.

3.3.4 Ply and vacuum bag bridging

Bridging is an effect of unsuccessful draping where the reinforcement [24,32] and/or layers of the vacuum bag [27,33,34] are not in contact with the mold surface potentially caused by improper lay-up and debulking. Some bridging is often inevitable and causes wrinkling [1].

Bridging can be observed in smaller corner radii with a longer limb length (distance from the corner to a free edge) which would allow for a necessary slip of the plies into the corner, transitions of ply numbers (tapered laminates), resulting from gaps and overlaps. At low resin viscosities and high consolidation pressures, matrix migration can be observed in bridged areas in radii when resin is squeezed into the outer area. Friedrich et al. [23] explains this phenomenon as a lack of time for the inter-ply slip deformation mechanism to occur. Incorrectly placed vacuum bags can cause wrinkles to form in female corners when the vacuum bag is bridged [33]. Flexible silicon rubber pads or "dog ears" can be used to avoid bag bridging compared to a conventional vacuum bag lay-up [27,34]. The vacuum bag may not be able to follow the deformation that occurs during the consolidation of the laminate. This influence is increased when prepreg systems with a high bulk factor are used, e.g. semi-impregnated out-of-autoclave (OOA) prepregs. For this reason, there may be a lack of pressure in the resin in the corner area, leading to void growth. When atmospheric pressure prevails on the outside, the vacuum bag does not deform and does not slip due to the low compaction pressure. Increased consolidation pressures in autoclave processes can cause the vacuum bag to slip and reduce the amount of bridging, although shear forces due to the friction between vacuum bag and plies may force the layers into the corner radius thus leading to fiber waviness.

3.4 Interaction between tool-ply and ply-ply

Tool-ply and ply-ply interactions can be described by viscous friction laws. The sliding between ply-to-ply and ply-to-tool is affected at the interface by the coefficient of friction [16]. High frictional forces can cause in-plane buckling of the fiber tows and out-of-plane wrinkling of the fabric. The parameters that influence the friction coefficients are mold surface roughness, fiber tow surface roughness, presence of binders, presence of liquid resin, and processing temperature. Tack and drapeability [16] are also important quality characteristics of prepregs. Tack or stickiness is defined as the ability of a partially cured prepreg layer to adhere to the mold surface and to another partially cured prepreg layer. Prepreg with too little resin on the surfaces has low tack and may need to be heated to increase its tack during layup. On the other hand, if the surfaces are resin rich and there is less resin inside (e.g. vacuum channels in out-of-autoclave prepregs), the prepreg may separate at the center during the layup process. Drapeability is defined as the ability of the prepreg to conform to the mold surface without fiber distortion, movement, and out-of-plane buckling.

3.4.1 Inter-ply slippage (Slipping ability of layers) (Coefficient of friction)

The formation of waviness is dependent on the frictional behavior between the plies. If the friction is sufficiently low, the excess length (limb length) can be dissipated into the rest of the part by shearing in the layer interphase. At the beginning of the curing process, the shear and Young´s moduli of the resin are very low [35]. These may decrease even further when temperature increases and viscosity drops in the first step allow a certain amount of ply movement to occur before cross-linking increases the material properties. Inter-ply slip or inter-laminar slip [23,36–38] is a relative shear movement of two adjacent laminate layers. It occurs when layers slip or slide relative to each other when the flat prepreg stack is deformed over a single curved surface, e.g. a corner radius. In liquid composite molding processes, the inter-ply slip is supported by the liquid resin, which acts as a lubricant between adjacent plies, especially in low viscosity resins. According to [36], inter-ply slippage is considered to be the principal mechanism that prevents the occurrence of wrinkles during the shape change. Inter-ply slip can also occur between plies of woven fabric [39]. Woven fabrics are more extensible compared to unidirectional materials due to the undulations which allow a certain straightening of the fibers when forming over a radius. According to Murtagh et al. [39], inter-ply slip only occurs once the fiber tows have been straightened and become inextensible. Conversely, the crimped nature of the tows also means that the plies exposed to compressive stress tend to buckle. Stresses are, according to [40], a function of time, temperature and processing rate. The stress needed to induce inter-ply slippage and shear, decreases with increasing temperature and increases with increasing deformation rate [36]. The stresses during forming may be partially or fully relaxed by inter-laminar slippage, if given enough time to do so. However, if the forming velocity is too low in forming processes of reinforced thermoplastic materials, the actual temperature of the laminate may drop below a temperature level where inter-ply slip can no longer occur. In this case, the shear stress acting on the plies does not exceed the shear yield stress of the matrix material, which ultimately leads to fiber wrinkling at the compressed inner face of the bending.

3.4.2 CTE mismatch

The longitudinal stiffness of composites is much higher than the transverse stiffness, and the longitudinal coefficient of thermal expansion (CTE) is much lower than the transverse CTE [6]. The anisotropy of composite materials may be an advantage from a structural point of view, but also a main reason for process-induced deformations. The curing of high performance composites typically happens at elevated temperatures. Especially the cool-down process/rate leads to a significant CTE mismatch. Residual stresses can also occur due to a CTE difference between fiber and matrix [6,41]. Several studies [24,42] have identified the CTE mismatch and, consequently, the tool/part friction (slippage) as the main phenomena leading to fiber wrinkling. Additionally, Kugler and Moon [42] have shown the significant influence of the cooling rate and length. The prediction of instabilities originating from the differences in CTE is very complex, as shown in the studies of Dodwell et al. [8] and Belnoue et al. [43].

3.5 Lay-up sequence

In general, the lay-up sequence has a strong influence on the formability and resulting out-of-plane deformations. [44] reported that the stacking sequence has a strong influence on the formability of thermo-stamped parts. They observed out-of-plane wrinkles and ply separation in quasi-isotropic 0/90/45/−45 laminates, but not in [0/90] laminates. Hallander et al. [45] stated also that [0/90] and [45/-45] lay-ups in a UD prepreg are less senstitive to out-of-plane defects compared to a quasi-isotropic lay-up. The results of forming studies carried out by Friedrich et al. [23] have shown that the instabilities such as in-plane wrinkles and out-of-plane buckles, only occur in distinctive areas of diaphragm-formed parts which can be directly related to the lay-up of the laminate.

3.5.1 Gaps and overlaps

The phenomenon of gaps and overlaps is strongly related to automated fiber placement (AFP) and automated tape laying (ATL) processes and its steering methods. When locally placing tape layers in a laminate according to the load path, the resulting laminate typically consists of a large number of gaps and overlaps, which can be of different sizes and complex combinations [46]. These effects on the mechanical properties of the laminate are still under investigation and the existing results spread between 5-30 % [19,47]. Lukaszewicz et al. [48] reported that the tolerance in head movement, steered fibers and row width variations contributes to gaps and overlaps. Lan et al. [49,50] studied the mechanical properties of AFP laminates containing gaps and overlaps, which were cured with and without caul plates. The use of caul plates is critical during polymerization, as it can prevent thickness variations and allows defects to heal. Belnoue et al. [46] stated that the influence on the final fiber path and ply geometry from gaps and overlaps is not their nominal as-deposited position, but a function of what happens to the laminate in the subsequent processes, such as debulking or consolidation. This should be taken into account in manufacturing practices and the analysis of such defects. According to Elhajjar et al. [33], a special form of gaps which may lead to wrinkles can be found in sandwich structures which are resulting from core splicing.

3.5.2 Ply drops in tapered laminates

The majority of real composite components contain ply terminations, also called ply drops in tapered laminates, within the structure due to varying numbers of plies between two adjacent regions of the part. Examples of tapered composites containing fiber waviness and their mechanical evaluation can be found in [51]. Design rules for thickness transitions are generally well established [5]. However, Hart-Smith [52] stated, that poorly made ply drop regions, where the consolidation of the ply drop region can lead to additional fiber waviness, can have a more negatively effect on the components to properties than a set of well-made external ply drops. The mechanism of wave formation is similar to that in a corner radius as described in Section 3.2.4. The change in part thickness generates an excess length of the plies which can be dissipated by slipping between the plies or, if the friction between the layers is too high, by an out-of-plane movement that accommodates for this additional length. According to Potter et al. [5], fiber wrinkling tends to occur when the fibers are deformed out-of-plane to match the ply edges of the dropped plies. Belnoue et al. [43] investigated the wrinkle formation in tapered laminates under double-sided rigid tooling due to variabilities in the ply thickness, which would lead to a mismatch between mold and preform. The thickness variation of the laminate upon consolidation is responsible for the generation of excess length. Processed in an autoclave using single-sided tooling and a vacuum bag, the tapered specimen would not exhibit any substantial wrinkles.

3.6 Textile architecture

3.6.1 Inherent undulations in woven and braided fabrics

Undulations or crimped fibers are inherent to the internal structure of woven and braided fabrics due to the textile manufacturing processes with recurring undulations of warp and weft fiber bundles [53] and therefore have to be considered as a feature rather than a defect. The resulting uniform undulation depends on the selected weaving architecture, i.e. the most common weaving patterns plain, twill and satin. 3D fabrics that are reinforced through the thickness can be used to improve inter-laminar properties of the composite part. However, these interlocks induce additional distortions in the internal architecture, such as in-plane waviness, and reduce the mechanical properties [54] similar to stitches in non-crimped fabrics, as described in Section 3.6.3.

3.6.2 Shear locking angle of woven fabrics

Considering deformations on the micro/meso scale, in-plane and inter-ply shear, have been identified by several researchers as the important parameters governing the formation of aligned fiber composites [13,55]. Before shearing fabrics, the yarns are initially orthogonal to each other. As the intra-ply shear is initiated, the yarns begin to rotate and slide over each other. The friction between the yarns at the crossovers and viscous drag if a liquid resin is present contributes to the resistance to shear deformation, which is still relatively low at this level of loading. As loading increases, the adjacent yarns come in contact and press against each other, resulting in yarn compaction and increased shear stiffness. When the load is further increased, the yarns become locked. Loading beyond this locking point causes out-of-plane buckling of the fabric and the resulting deformation is not only due to shearing. The load increases very quickly to a high value after the locking of the yarns.[13,16]

The shear locking angle is mainly a function of the weave style and thickness of the tow. Beyond this angle, further deformation may cause out-of-plane buckling in the part. By applying tension to the reinforcement, it is possible to achieve a higher shear deformation, than one could expect if only the locking angle is considered. As a result, an increase in the tension applied on the interlock fabric tends to delay the onset of wrinkles [56].

3.6.3 Stitches in non-crimped fabrics

Even if the term non-crimped fabrics (NCFs) [57,58] refers to semi-finished fiber products that do not contain any fiber misalignment, they usually contain small level fiber waviness due to stitches or binder yarns. This is an inherent feature of the material similar to undulations in woven fabrics. Amongst many other studies, Cao et al. [58] numerically studied the effect of in-plane fiber distortions in quadriaxial non-crimped fabrics (QNCF) induced by the stitching yarn on the mechanical properties using meso-scale finite element simulations. The effects of in-plane fiber distortions on the longitudinal elastic modulus were found to be insignificant. The modulus of the QNCF lamina resulted in a difference of 3.34% compared to the un-stitched composite with the same UD type. Cao also stated that this conclusion on the stiffness of QNCF composites is different from the open structure NCF composite in which the stitching may reduce in-plane elastic properties by 10%-20%.

3.6.4 Stitches in dry fiber placements

Using dry tows in tailored fiber placement (TFP) methods [59,60] overcomes the disadvantages of the pre-impregnated tape placement techniques. Both methods use in-plane bending deformation of the tow/tape to achieve a curved tow path, but the dry and typically thinner tows in TFP tend to bend or shear much easier. Because dry tows do not have tackiness, they cannot be deposited without a suitable fixing method. The most common method uses an embroidery technique in which a numerically controlled stitching head stitches the tows onto a backup fabric, generally used together with an additional backup felt, to hold the preform together.

Similar to ATL, curved tow paths can lead to local buckling of the fibers induced by the in-plane bending deformations. Additionally, the fabric may be wrinkled if the tension of the stitching yarn is too high and the softness of the backup felt allows the stitching yarn to move upward. In this case, the placed tows cannot be firmly attached to the substrate. Machine heads that operate without a tow feeding mechanism have to pull the tow by applying slight tension. This tension force makes the placed tow move toward the origin of the curvature under the influence of the looseness of the stitching yarn, which increases the buckling intensity of the fibers inside the tow path and significantly enlarges the tow gap area outside the tow path. [59]

To overcome the problem of fiber waviness induced by stitches in TFP, Hazra et al. [61] investigated the applicability of a soluble stitching yarn. The in-plane fiber misalignment was observed to still exist, but the out-of-plane crimp was reduced.

3.7 Foreign objects

3.7.1 Intended (e.g. optical sensors, pins, inserts)

In many cases, foreign objects may be intentionally integrated into the material, e.g. optical sensors for strain measurements or health monitoring, metal pins for joining parts, or inserts, which in turn can interfere with the fiber orientation inevitably causing local fiber waviness. The wave characteristic depends on the size (diameter) of the embedded object. Embedded optical sensors lead to out-of-plane waviness, whereas stitches or pins lead to in-plane waviness. The diameter of optical Fiber Bragg Grating (FBG) sensors ranges from 52 µm to 125 µm [62]. The diameter of optical fiber sensors is a multiple compared to the most commonly used reinforcement fibers (glass: 5–20 µm, carbon: 5–10 µm). The reduction of the optical fiber diameter minimizes the distortion of the reinforcement fibers. However, not only size difference between optical and reinforcement fibers, but also the type of composite material used (unidirectional, woven fabric, stitched, braided, etc.) and the relative orientation of the optical fiber with respect to the reinforcement fibers influences the distortion [63]. Several studies [63–65] have shown that there is little effect on the load carrying capacity of composites as long as small diameter optical fibers are embedded between similar layers, i.e. avoiding stress concentrations when the optical fiber is predominantly oriented in the fiber direction of these layers.

3.7.2 Unintended (e.g. foils, blades etc.)

Unintentionally embedded foreign objects, like release film, tapes and tools (knife blades) are serious flaws during ply collation [34,66]. These defects lead to fiber waviness, similar to the intentionally embedded sensors or inserts, but can be avoided by strict compliance with process instructions and stringent quality controls.

3.8 Flow induced waviness

3.8.1 Fiber wash-out

If, in infiltration processes, the resin feed velocity and/or the injection pressure is too high, the resin viscosity is not low enough, or the fibers are only held loose due to low fiber volume fractions or poor tolerances of the mold, the fibers may be deformed by the flow of the resin [33,34]. Hallander et al. [45] stated, that materials with lower inter-ply friction are also more sensitive to fiber wash-out. In infiltration processes, especially when using higher pressures such as in Resin Transfer Molding (RTM), the injected resin can force the fibers to be locally ´washed´ mainly occurring at the injection port and also wholescale movements of plies leading to wavy regions and resin rich zones [1,67]. Due to the compaction of the layers in thickness direction by double-sided RTM molds, the layers are more prone to in-plane waviness. A basic method used to prevent fiber waviness is to choose optimized process parameters to minimize or totally eliminate fiber washing. By carefully choosing the LCM process parameters such as resin viscosity, pressure, and molding temperature, fiber movement during resin injection can be minimized [68].

3.8.2 Hydraulic effects (squeezing, transverse flow)

In forming processes such as thermoforming or compression molding, a non-hydrostatic pressure, similar to RTM processes, can lead to a fiber movement away from its desired position and form a wave shaped misalignment. Squeeze flow [29] describes the transverse flow of the fiber/resin/voids mixture as a function of the pressure distribution across the tow to yield the reduction in height and the increase in width. Friedrich et al. [23] stated, that the local pressure gradients can arise from small variations in the laminate thickness and mold clearances. Further shear stresses that develop between the thermoplastic material and the mold surface may also result in transverse flow. According to [69], this squeezing mechanism typically occurs at low temperature and low pressure, until a locking of the material occurs, the point at which the fiber bed reaches a configuration where it no longer deform. The squeezing flow, i.e. the laminate, behaves as a highly viscous incompressible fluid, according to Hubert and Poursartip [70]. After that, a transition from transverse squeezing to bleeding takes place corresponding with a change from transverse resin flow direction to bleeding. In Hot Drape Forming (HDF), the usage of stiffer diaphragms increases the squeeze flow due to higher forming pressure, however, the risk of out-of-plane deformations, e.g. wrinkling, is reduced [14].

3.9 Cure induced waviness

Parlevliet [71] gives a comprehensive overview of residual stresses in composite materials and states that fiber waviness can be regarded as a defect which has formed due to residual stresses. In part I of the publication series by Parlevliet [72], three mechanical levels of residual stress formation were identified: micromechanical residual stresses (resulting from the shrinkage mismatch between the matrix and the fiber), interlaminar residual stresses (resulting from ply anisotropy in angle-ply composites) and residual stress gradients through the thickness (resulting from gradients in cooling rate, material density, thermal gradients, etc.).
One method used to prevent ply wrinkling during curing is to keep the laminate thickness below certain limits in order to minimize exothermal heat generation. In general, the curing should be carried out at carefully controlled temperature gradients to minimize differences in the thermal expansion.

3.9.1 Volumetric shrinkage

Another important aspect in processing composite materials is the cross-linking of the resin. Chemical reactions during the curing process lead to shrinkage. In contrast to the resin, fibers exhibit no chemical shrinkage. Deformations are likely induced by the CTE mismatch, described in Section 3.4.2, between fiber and matrix, and the curing shrinkage of resin. The exothermic reaction during curing and the corresponding shrinkage in thermoset systems, or physical shrinkage in fiber reinforced thermoplastics, affects the formation of sink marks which result in fiber waviness. The temperature changes experienced by the composite and the volumetric shrinkage of the matrix are also reported to induce waviness [42,71]. The fiber waviness can occur due to both the bulk factor and shrinkage in the thick-walled areas of transitions, e.g. T-joints.

3.9.2 Large temperature gradient in thick laminates

Besides the tool–part CTE mismatch, sufficiently high temperature gradients that are present through the thickness of the laminate can cause fiber waviness. Since thick laminates are prone to large temperature gradients throughout the thickness, wrinkling is often induced in thick laminates [71,73], e.g. those found in wind turbine blades. Parlevliet [71] concluded, that one of the effects of residual stresses is fiber waviness. The presence of sufficiently high thermal residual stresses can lead to fiber waviness during the curing due to a mismatch between the coefficients of thermal expansion of the composite constituents [42]. The difference between the coefficients of thermal expansion of fiber, matrix, and mold can be several orders of magnitude. This often leads to residual stresses in the composite during the cooling step of the process. When the fibers experience axial loads during processing, e.g. due to thermal residual stresses, while the matrix is unable to provide some level of transverse fiber support, then fiber waviness may be observed due to micro-buckling. Elevated cooling rates can lead to compressive stresses on the laminate surface, while slower cooling rates avoid significant temperature gradients through-the-thickness of the part and allow time for stresses to relax [42].

4. CLASSIFICATION SCHEME

The following section gives an overview of typically occurring wave shapes incorporated into a classification scheme.

4.1 Number and distribution of waves

Generally, waviness can be distinguished by whether there is a single wave, a multi-frequent (stochastic) or a mono-frequent (in-phase) distributed number of waves in the laminate (Figure 2). The occurrence of single or distributed waves can be attributed to the bending stiffness of the layers. Plies with higher bending stiffness tend to single wave formation, whereas low bending stiffness plies tend to form a higher number of waves.

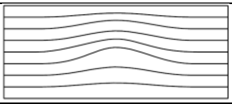
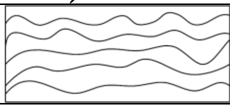
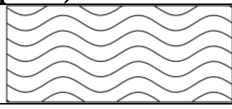
Single wave	**Multi-frequent (stochastic) distributed waves**	**Mono-frequent (in-phase) distributed waves**
		

Figure 2: Single vs. distributed waviness

4.2 Traditional differentiation of wave types - Constant or changing wave amplitude

Another general distinction between uniform and graded waviness (Figure 3) is often used in literature [74,75]. In graded waviness, unlike uniform waviness, the amplitude changes in the thickness direction of the laminate. Graded waviness is typically embedded in the laminate, whereas uniform waviness is more likely to be visible on the surface. However, uniform waviness can be also embedded, but occur only locally and not across the entire thickness.

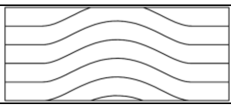
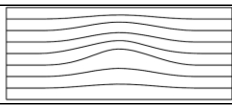
Uniform waviness	**Graded waviness**
	

Figure 3: Uniform vs. graded waviness

4.3 Phase characteristics of the wave form

The iso-phase model [76], depicted in Figure 4 (left), assumes all fibers to be in the same phase along the x-direction. Similar to uniform waviness, each small volume element of the composite between x and $x+dx$ is approximated by a unidirectional fiber composite, in which fibers are inclined at an angle θ to the x-axis. In contrast to that, the fiber orientation θ of the random-phase waviness, shown in Figure 4 (right), is randomly distributed at each x increment. Although the description of the random phase waviness is a rather mathematical one, this form of waviness may be caused by shear stresses in the thickness direction of the laminate.

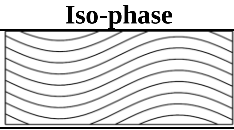
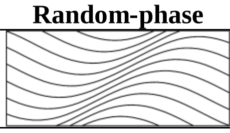
Iso-phase	**Random-phase**
	

Figure 4: Iso-phase vs. random-phase waviness

4.4 Visibility

In terms of detectability, outer visibility constitutes another classification (Figure 5). Embedded waves, i.e. not directly visible deviations of the fiber orientation from the outside surface, are more difficult to be detected compared to visible waves, due to differences in thickness t of the laminate or deviations from a planar surface.

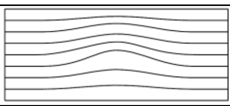
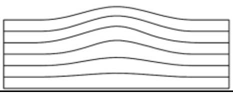
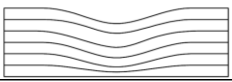
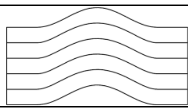
Embedded wave	**Visible wave**		
			
	Hump *(t = variable)*	Indention *(t = variable)*	Wave *(t = constant)*

Figure 5: Embedded vs. visible waves

4.5 Dimensional characteristics

With regard to the assessment of fiber waviness, the dimensional characteristic of waves is an important distinguishing feature. If the waviness changes one of its characteristics in the third spatial direction, this must also be taken into account in the design. Figure 6 shows a representation of a 2D wave (left) and a 3D wave (right), which often occurs, for example, in thermoforming processes in peripheral areas, i.e. drape run-out.

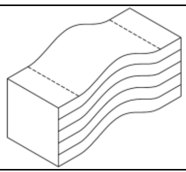
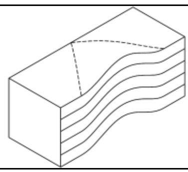
2D wave	**3D wave**
	

Figure 6: 2D vs. 3D waves

4.6 Continuity of layers/laminate

Fiber waviness frequently occurs in laminate transition areas with varying thicknesses resulting from ply-drops, or also through gaps and overlaps which are characteristically for automated fiber placement (AFP) processes. In AFP processes, the overlapping tapes are forced to move upwards into adjacent gaps during the consolidation step resulting in fiber waviness. Another case may cause the generation of out-of-plane fiber waviness, namely stepped laminates in combination with soft tooling. Especially when the step height is too high, the bridged bag causes a non-uniform pressure on the laminate areas leading to fiber waviness. This is typical for stringer edges or runouts in stiffened panels. In general, these types of fiber waviness occur due to non-continuous layers compared to waviness in continuous layers or laminates (Figure 7).

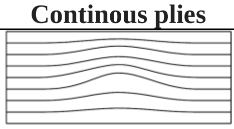
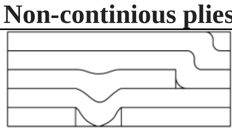
Continous plies	**Non-continious plies**
	 Gaps and overlaps

Figure 7: Waves at continuous vs. non-continuous plies

4.7 Position of the wavy region in the laminate

The ratio of wavy plies to the total number of plies represents a characteristic factor of local waviness where only a part of the laminate is wrinkled and the remaining layers are oriented according to the design (Figure 8). Multidirectional laminates may be more prone to local fiber waviness due to varying (bending) stiffnesses of the plies. Camanho et al. [77] introduced strength correction factors to account for this position as well as the thickness of the layer.

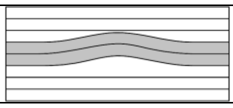
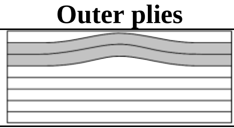
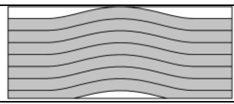
Centered	**Outer plies**	**Whole laminate**
		

Figure 8: Position of the wavy layers in the laminate

4.8 Phase characteristics of the material

For the resolution of fiber and matrix areas in the laminate the microscopic level is investigated. Manufacturing effects, such as bridging or fiber washing, can result in areas without fiber material that can be filled with excess resin. These areas are visible to the naked eye in many cases, i.e. in bridged corner radii, and are therefore referred to as macroscopic phases by resin accumulation. Especially in manual production steps, such as hand lay-ups, unwanted foreign bodies embedded in the laminate, such as carrier foils, knife blades, etc., can cause wrinkles which in turn can lead to additionally accumulations of resin in this area. This also leads to macroscopically different phases, in this case by foreign material. A schematic overview of this classification is shown in Figure 9.

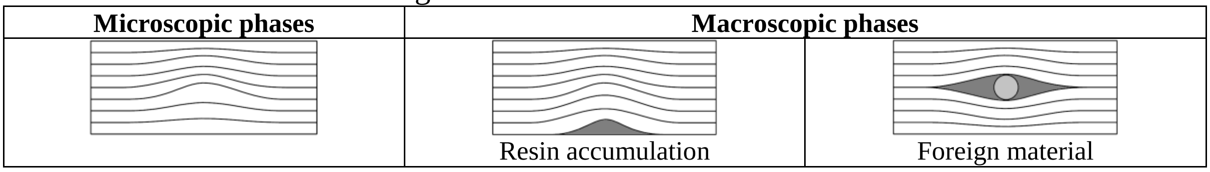


Figure 9: Microscopic vs. macroscopic distributed phases in wavy regions

4.9 Level of influence

The influence of wavy layers strongly depends on the affected thickness of the laminate (Figure 10). Especially in thin-walled laminates with a correspondingly large degree of waviness ($t << A$), in addition to the influences on the material properties, structural influences [78] become apparent. In such cases, a complex mix of both material and structural type behavior leads to strongly nonlinear geometric constraints, requiring the calculation of stresses resulting from the bending of the wave.

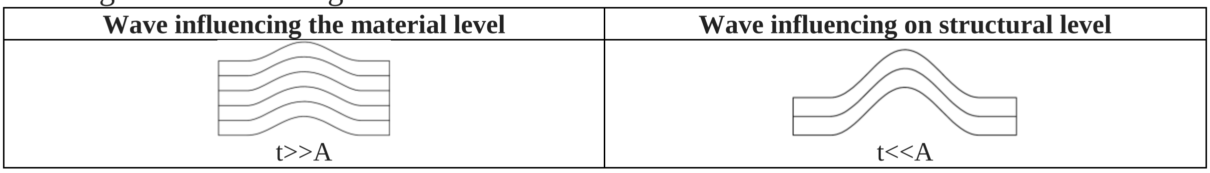


Figure 10: Material vs. structural level

4.10 Geometric position of the wavy region in the part

There is a growing interest in the use of thick walled composite parts to replace complex metallic fittings for specific applications. These parts often have quite complex geometries and consist of radii, transitions and varying wall thicknesses which are prone to fiber waviness. The wave formation mechanisms stated below are typical for thick-walled laminates, where the large amount of material constrains its movement, respectively influences the exothermic curing behavior. The consolidation of a ply stack over an external radius is a well-known cause of wavy regions. Fiber waviness in areas of radii, transitions, and brackets, as shown in Figure 11 on the right, are often due to the bulk factor of dry fiber semi-finished products after preforming thick laminates. When the plies are consolidated under elevated external pressure the laminate thickness reduces, resulting in an excess length of the material. In addition to that, the exothermic reaction during curing and the corresponding shrinkage in thermoset systems, or physical shrinkage in fiber reinforced thermoplastics, affects the formation of sink marks and the resulting fiber waviness. The fiber waviness in T-joints (right, center) can occur due to both the bulk factor and shrinkage in the thick-walled areas of the transition, and furthermore in the final compaction process when layers may move as the RTM mold is closed.

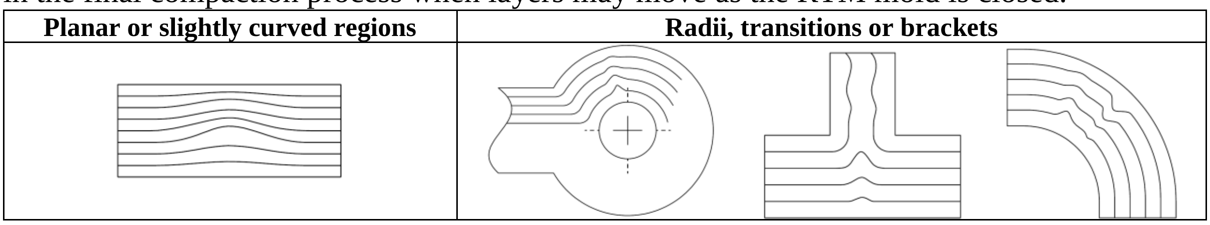


Figure 11: Waves in flat or slightly curved areas vs. waves in radii, transitions or brackets

5. CONCLUSIONS

This paper gives an overview of various types of out-of-plane fiber waviness (wrinkles) and their origins. Since the manufacturing processes of composite materials are very different, a variety of waviness types may occur. A classification scheme was developed to classify different types of waviness and to trace them back to their possible cause. Among others, process parameters (e.g. temperature, pressure and deformation rate), the selection of the fiber and tooling material and its properties (e.g. CTE) as well as the complexity of the geometry of the final component are the main parameters that influence the occurrence of fiber waviness. These influencing parameters often affect each other and a distinct assignment of a resulting waviness to a specific origin can be difficult. Nevertheless, this work contributes to the understanding of the formation of fiber waviness and provides a guideline for reducing or, in the best case, completely avoiding them.

6. ACKNOWLEDGEMENTS

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