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Citation for the original published paper (version of record):

Toyoda, D., Wärmefjord, K., Söderberg, R. (2023). Challenges in geometry assurance for composites manufacturing. Journal of Computing and Information Science in Engineering, 23(5).
http://dx.doi.org/10.1115/1.4057021

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| *First* | *Last* |

ASME Paper Title: Challenges in geometry assurance for composites manufacturing

Authors: Diogo Toyoda, Kristina Wärmefjord, Rikard Söderberg

ASME Journal Title: Journal of Computing and Information Science in Engineering

Volume/Issue: 23/5

Date of Publication (VOR* Online): 2023/03/29

ASME Digital Collection URL: https://asmedigitalcollection.asme.org/computingengineering/article/23/5/051007/11
es-in-Geometry-Assurance-for-Composites

DOI: https://doi.org/10.1115/1.4057021

*VOR (version of record)

Journal of Computing and Information Science in Engineering. Received July 18, 2022;
Accepted manuscript posted February 21, 2023. doi:10.1115/1.4057021

# Challenges in geometry assurance for composites manufacturing

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*Composite materials are well known for their high strength-to-weight ratio, but their unique manufacturing process presents some challenges and is a source of geometric variations. To minimize the effects of such variations in the final product is the main goal of geometry assurance. To achieve that, variation simulation tools are used to predict variations and optimize manufacturing parameters, to ensure a robust design. In this paper, the most common variation sources linked to the manufacturing process are discussed. Then, variation simulation tools and features for parts and assemblies are presented. Applicability for composites of existing tools and other studies for metallic parts is compared. Finally, future challenges in variation simulation for composites are discussed.*

## 1 INTRODUCTION

Towards a more sustainable future, it is primordial to reduce our carbon footprint. In many industries, such as aerospace and automotive, this means, among other solutions, using lightweight materials. This reduces fuel consumption and, consequently, $CO_2$ emissions. In this regard, composite materials are well known for their high strength-to-weight ratio [1].

Geometric variation is inherent to all manufacturing processes, implying that a real dimension will not be equal to the nominal dimension at all times. Therefore, a manufacturing dimension is described as a nominal value and a expected acceptable range (tolerance). Ideally, tolerances are defined in a top-down manner, meaning that overall product requirements are broken down, up to the component level [2].

Simply put, geometric variation becomes a defect when it results in an out-of-tolerance dimension. Therefore, it may become difficult to manufacture a part within tolerance if it was designed without an understanding of the variations involved [3]. In an assembly, composed by several parts, the geometric variation comes from variation in these parts and from the assembly process [4].

In geometry assurance, the goal is to have a robust design, aiming to minimize the effects of geometric variation (from parts and assemblies) in the final product [5]. To assess the robustness of an assembly in early stages of the development process, one can use variation simulation tools [6]. It is important to improve variation simulation tools and methods for composites, since this will reduce the scrap and rework rates in the manufacturing process, consequently reducing the general costs for using this type of material. This will also improve the predictability of the manufacturing process for composites.

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Journal of Computing and Information Science in Engineering. Received July 18, 2022;
Accepted manuscript posted February 21, 2023. doi:10.1115/1.4057021

### 1.1 Scope of the paper

Since composites are more prone to variation, this paper aims to map existing tools and methods and future challenges in geometry assurance for composite parts and assemblies. In section 2, composite materials are introduced and in section 3, typical manufacturing methods are described. Common variation sources for each manufacturing step are discussed in section 4. Variation sources from incoming raw material and molds are not considered in this paper. Section 5 analyses geometry assurance tools for variation simulation and section 6 summarizes the future challenges in geometry assurance for composite parts and assemblies. The conclusion, section 7, highlights the paper importance and contribution.

## 2 COMPOSITE MATERIALS

A composite material, or just composite, can be defined as a combination of two or more materials that results in better properties than those of the components alone. However, differently from a metal alloy, each component retains its separate chemical, physical, and mechanical properties [7].

For high-performance purposes, what is called advanced composite materials were developed. Advanced composites are strong, lightweight, engineered materials consisting of high-performance reinforcing fibres embedded in a polymeric matrix, to form a ply (or layer). Several plies are then stacked at various orientations to form a laminate [8].

Due to the different orientations of each ply, composites are anisotropic, i.e., properties are different when measured along axes in different directions [9]. This is an advantage from the strength point of view, since it is possible to tailor the laminate strength and stiffness according to the load pattern [10]. However, its behavior is more difficult to predict and simulate.

In the aerospace industry, carbon fiber reinforced polymer (CFRP) is widely used [11], due to its outstanding strength, corrosion and fatigue properties. CFRP laminates are basically composed of unidirectional or bidirectional continuous fiber fabrics as reinforcement, and epoxy resin as matrix.

Honeycomb or foam cores are used in the laminate when the stiffness of the structure has to be increased at a low weight penalty. Placing two high-strength skins, one in each side of the core, results in the so-called sandwich structures. The core acts like an I-beam's web, providing a lightweight "separator" between the load-bearing skins [12].

Other elements, such as adhesive films, metallic meshes and finishing may be added to the laminate, to improve some properties, appearance or manufacturability.

## 3 COMPOSITES MANUFACTURING

### 3.1 Part manufacturing

A typical manufacturing process of an advanced composite part basically involves the following steps (see Fig. 1): (a) cutting the plies, (b) placing the plies over the mold to form the laminate, (c) infusing the resin (if necessary), (d) compacting, (e) curing and (f) machining edges, cutouts and holes.

Raw material for composite parts are usually supplied in wide fabric rolls. The plies are then cut in their final shape, which can be done manually or using an automated ply cutting table. The latter consists of a conveyor belt with a cutting tool that runs above it.

The plies are then laid-up over the mold, manually or using numerically controlled machines, in processes called Automated Fiber Placement (AFP) and Automated Tape Layup (ATL), respecting defined layer orientations. For the AFP and ATL processes, the cutting and resin infusion processes are not necessary, since the machines place pre-impregnated (*prepreg*) fiber tows and strips, respectively, directly into the mold.

If prepreg fibers are not used, it is necessary to infuse the resin in a separate step, either manually or by processes like resin transfer moulding (RTM) [13] or vacuum infusion processing (VIP).

Compaction is usually achieved by using a vacuum bag, in which the laminate is sealed in a plastic bag. Then, vacuum is applied, forcing air, humidity and excess resin out of the bag.

The curing process can be performed at room temperature, in an autoclave or in an oven. An autoclave, besides the controlled temperature an oven can deliver, also applies a positive pressure, improving the consolidation of the separate plies into a solid laminate.

Normally the laminate is intentionally larger than the final part, so the edges have to be trimmed to result in the final contour. Besides, internal cutouts and holes are performed in this step. Computer Numerical Control (CNC) machines are typically used for this step.

### 3.2 Assembly manufacturing

Composite materials allow the manufacturing of more complex geometries, reducing the number of components of an assembly, compared to metal parts. This also reduces the overlapping material necessary for a joint using, for example, rivets or bolts, consequently reducing weight.

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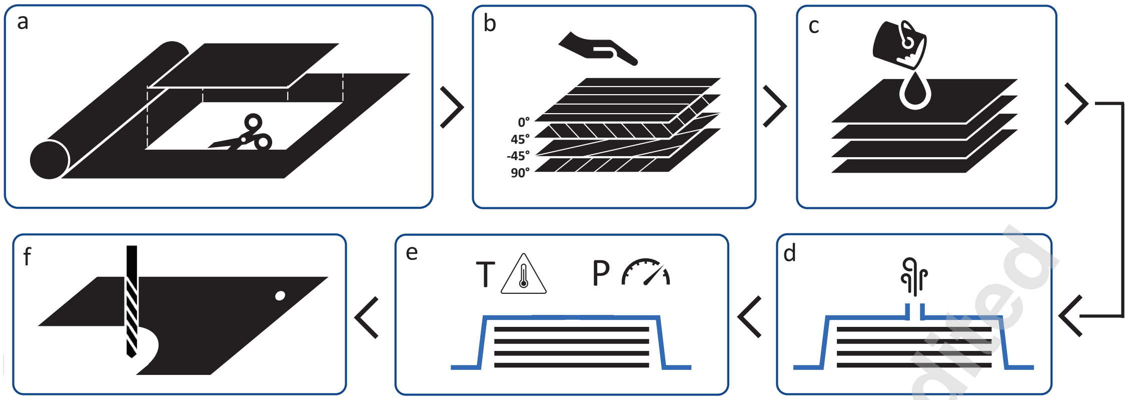

Fig. 1. Manufacturing steps: (a) cutting, (b) placing, (c) infusing the resin, (d) compacting, (e) curing and (f) machining

However, assemblies are still needed and, to position each part, a fixture is normally used. The fixture for a composite assembly follow the same design principles as of one for metallic parts, using clamps, stops, holes and slots to fixate each part. To join parts together, the most common methods for composite assemblies are rivets, bolts and bonding.

For riveted joints, usually pre-holes are drilled in the assembly components, using robots or drilling jigs. Temporary fasteners, e.g. *clecos* [14], are used to secure the holes alignment, also applying small forces to close eventual gaps between the parts. If the gaps remain, they are measured to allow shims to be manufactured. The temporary fasteners are removed, the parts are removed from the fixture, cleaned and sealed. The shims are installed in the interface and then the holes are reamed to the final diameter, so the final fastener can be installed.

Bolted joints are usually used in highly loaded joints, especially in tension. They are also used for removable or replaceable parts, such as inspection doors, fairings and control surfaces of an aircraft. In this case, for maintainability and interchangeability purposes, these parts are ready for installation and, therefore, come with the final holes already drilled.

Composite parts can also be joined by secondary bonding, co-curing and co-bonding. Secondary bonding is the adhesive joining of two pre-cured parts. Co-curing is the simultaneous cure of two non-cured parts in contact with an adhesive film. Co-bonding is the process where a cured structure is put against an uncured laminate with an adhesive at the interface [15].

## 4 GEOMETRIC VARIATION SOURCES

Geometric variation is inherent in any manufacturing process, causing deviations that may affect functional and esthetical requirements. Every step of the manufacturing process is a potential source of geometric variations. For composite parts, some of these steps are manual, especially for low volume production, or when complex geometries are required. Consequently, the process is prone to more variation and errors, when compared to a metallic part (machined or formed sheetmetal). As mentioned above, geometric variation is inevitable, but only becomes a defect when getting out of the specified acceptable range of variation (tolerance).

In [3], a non-exhaustive list of more than 60 variability sources was compiled for a specific manufacturing process. It is hard to tell the root cause of every variation, since sometimes it is a combination of several factors. In the next section, some common variation sources in each manufacturing step are discussed. The selection of variation sources is focused on the ones related to the future challenges in the field (discussed in section 6) and is not an exhaustive list of variation sources.

### 4.1 Cutting the plies

When an automated ply cutting table is used, accurate contours and orientations are achieved, given the machine is properly maintained and operated. When cut manually, however, more variation is expected in both contour and orientation.

### 4.2 Placing the plies

Besides ply orientation variations from incoming material or during the ply cutting process, the final ply orientation will also be affected by the precision in which the plies are positioned/oriented in the mold. When the plies are placed by automated processes like ATL and AFP, a high precision is expected. In manual layup, however, there can be more variations while positioning the layers.

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To reduce them, the ply positioning can be aided by laser projections on the mold [16].

Draping, that can be described as the fabric's ability to form over 3D shapes without cutting or using undue force [17], is especially challenging for complex-shaped parts, with double curvature, sharp angles or protruding details. This can generate wrinkles and differences between the theoretical ply orientations and the real ones [18].

Narrow molds, deep molds, or molds with sharp inside corners can cause the so-called *bridging*, see Fig. 2a, resulting in a void in the laminate, or resin-rich corners, affecting the form and performance of the final part.

### 4.3 Compacting

Compaction is intended to be uniform all over the part. The consequence of non-uniform compaction is resin flowing to low compacted areas, creating resin rich areas and dry spots. Besides structural problems, such as porosity, voids and discrepant fiber-to-resin ratio, this can also geometrically affect the part, causing variations in thickness and form [20].

The vacuum bagging process is highly dependable on the labor experience and is a source of many geometric variations. The most obvious failure is leakage, that will prevent the proper compaction of the laminate and possibly leak resin.

Depending on the part complexity, pleats need to be created in the bag, to help accommodating the bag in curved areas. Pleats positioning and execution are difficult to perform and replicate, depending on craftsmanship and experience of the laminator. If not performed properly, pleats are potential sources of air pockets between the bag and the laminate. Other source of air pockets is bridging between the laminate and the bag, similar to the bridging between the laminate and the mold (Fig. 2a). Likewise, air pockets will not compact the laminate evenly, incurring in the forementioned issues.

### 4.4 Curing

Due to the anisotropic behavior of composite materials, internal stresses build-up during the curing process coupled with asymmetries in the laminate result in geometric variations [21]. Another source of variations is the tool-part interaction, in which differences in the coefficient of thermal expansion (CTE) between the part and the tool induce shear stresses in the interface [22]. These variations are usually referred as spring-in and warpage. Spring-in, for a profile, is the difference between the actual angle and the designed angle whereas warpage denotes the deviation of a nominally plane area from evenness [23].

To reduce these effects, the laminate should be balanced, symmetric and quasi-isotropic. A balanced laminate means having layers with positive angles balanced by negative ones. A symmetric laminate has identical layer orientations above and below the mid-surface. Quasi-isotropy can be reached by having layers in different orientations [24].

However, even for balanced and symmetric laminates, there can be geometric variations related to through-thickness fiber-to-resin ratio gradients. A ply closer to the tool has a lower fiber volume fraction. Fiber volume affects the local CTE, and a different CTE between the lower and upper sides of the laminate results in warpage in flat parts [25]. A similar issue appears when bridging occurs, causing resin-rich corners with fiber volume gradient in the trough-thickness direction. The effect is spring-in of the flange.

During curing, the viscosity of the resin decreases before consolidation [26]. This behavior facilitates one, several layers or the core to slide in relation to the rest of the laminate, affecting not only the performance but also the geometry of the final part.

Other issue that appears in this step is core crush. It is caused by the collapse of the core, when pressure is excessive in its weak lateral directions [27]. It affects the performance and the form of the part. One way to prevent this from happening is performing a pre-cure of the core, using a layer of film adhesive on both sides, a process called core stabilization. In [28], it is shown that core stabilization reduces core deformation.

### 4.5 Machining

The machining process is usually performed with the part in a different fixture from which the part was laminated and cured. Therefore, there can be variations in this positioning, leading to variation in contour, holes and cutouts positioning.

### 4.6 Assembly

To position each part during assembly, a fixture is normally used. As any other manufactured part, the fixture is not free of positioning and geometric variations, transmitting them to the assembly. It is important to have a good fixture design, to avoid amplifying errors from the fixture and from each part, resulting in large variations in the final product [29].

When non-nominal parts are clamped in the assembly fixture, induced stresses deform the parts, forcing them to the intended positions in the fixture. After the

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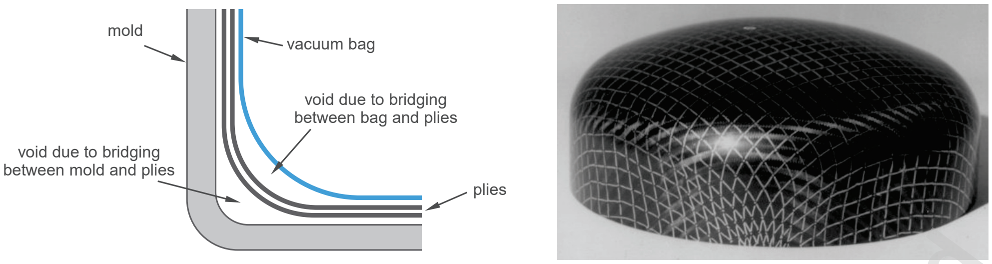

Fig. 2. (a) Bridging; (b) Shearing caused by draping [19]

temporary fasteners are installed, gaps between the parts are checked and, if excessive, shims are installed to fill them in, to avoid induced stresses from the fastener installation and securing that the parts will be in contact after fastening. After installation of the final fasteners, the assembly is released from the fixture, allowing it to spring back.

Since it is not possible to install all fasteners at the same time, after each fastener installation, stresses are induced in the structure, deforming it. This deformation is different depending on the fastening sequence, also affecting the final geometry differently.

## 5 GEOMETRY ASSURANCE

Geometry assurance encompasses all activities aiming to minimize the effect of geometric variation in the final product, in all phases of the development process. Since, in general, tighter tolerances result in more expensive products, geometry assurance focuses on balancing functional and quality aspects with manufacturing constraints and cost aspects [5].

In order to predict the geometric variation in a part or assembly, variation simulations can be performed before productions starts. The challenge is to have models and simulations that are representative of the actual conditions and processes, providing meaningful results. This is particularly complicated for composite parts, where more parameters influence the part manufacturing process, but it is essential to include as many as possible of these parameters in the simulations [30]. The geometric variation in the parts will stack up to variations from the assembly process, resulting in the geometric variation at the product level.

Direct Monte Carlo (DMC) simulation is often used for variation simulations. In this approach, the chosen input parameters are randomly generated, considering their typical distribution, e.g. normal distribution, and the resulting dimension of interest is computed. By repeating this computation, the distribution of the dimension in question can be approximated [31]. The more repetitions are performed, the more accurate the approximation is, at the expense of simulation time. There are several commercial software suitable for variation simulation, known as CAT (Computer Aided Tolerancing) software, such as 3DCS [32] and RD&T [33].

Table 1. References summary

| | Part | Assembly |
|---|---|---|
| Fiber orientation | [34] | [4, 35, 36] |
| Thickness | [37–41] | [4, 35] |
| Part geometry<br>Part variation | [38, 41] | [4, 35, 36, 42] |
| Fixture variation | - | [4, 35, 42] |
| Layup | [37, 38, 40, 43] | - |
| Cure temperature<br>Cure cycle | [41] | [42] |

In Tab. 1, the referenced papers related to composite materials in this section are summarized, according to the variation sources and if the variation analysis is performed in a part or assembly.

### 5.1 Variation simulation for parts

In the aerospace and automotive industries, it is not common to see variation simulation being performed in metallic parts (not assemblies). For formed metallic parts, forming simulations can be done to predict spring back after forming. However, those simulations are usually performed for manufacturability studies, such as tool compensation, and not for geometric variation purposes. Therefore, geometric variations in a metallic part are considered as input for the assembly variation simulation in the form of distributions based on experience or inspection data, not on simulation.

For composite parts, simulation variation is more relevant, due to variation sources that do not exist in metallic

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parts manufacturing. Consequently, it is more difficult to simulate the manufacturing process of a composite part. Some specific aspects of composite parts manufacturing simulation are discussed below.

### 5.1.1 *Layup and stacking sequence*

In [11], layup is defined as the ply composition (percentage of plies in each direction) of a laminate, and stacking sequence denotes the position of each ply in the laminate.

One of the main advantages in composites design is the possibility of tailoring the layup and stacking sequence according to the load's direction, optimizing structural efficiency. This sometimes implies different quantities and orientations of plies in different regions of the same part, making the modeling and simulation of these parts more complex.

For these reason, most of the studies in geometry assurance for composites use parts with the same layup and stacking sequence throughout the part, as in [34, 35, 37, 42, 44]. Therefore, more research is needed for parts that have regions with different layups and stacking sequences. There is also a lack of studies regarding variation simulation and geometry assurance in parts with a core in the layup (sandwich panels).

### 5.1.2 *Fiber orientation*

A dependence study between variation in the plies orientation and the spring-in angle was conducted in [34], comparing simulation and physical results of a L-shaped part. Variation simulation including fiber orientation analysis was performed in [4, 36, 38]. In [4], the results indicate that a variation of ±13° in fiber orientation and ±20% in thickness have a small impact on the geometric variation for the test case. However, the authors point out that more studies and tests are necessary to confirm the results.

There is also a challenge in representing the fiber orientations in the model. In finite element analysis (FEA) and CAT software, a global coordinate system defines the general orientation of each ply, where the orthogonal x, y and z axes usually determines the 0° orientation, the 90° orientation and the direction in which the layers will be stacked up, respectively. To determine the orientation of each mesh element, the global coordinate system is projected in these elements. Depending on the geometry of the part, this projected orientation can be very different from the actual orientation of the fiber in that point. This difference can affect deformation calculations and curing simulations. Although being a different matter, draping simulation can reduce this difference, by overriding the projected orientations with the results of the simulation.

### 5.1.3 *Draping*

Draping, as stated before, is the fabric's ability to form over 3D shapes without cutting or using undue force, and can affect the ply orientation. In a 0/90° bidirectional fabric, for example, the two originally perpendicular fiber orientations are affected by shearing, changing the angle between them, as seen in Fig. 2b. There exist a limit on the amount of shearing a fabric can handle, referred to as *locking angle*. Shearing beyond this angle may result in wrinkles [45].

Draping simulation is the subject of several studies, that were reviewed in [46], mostly related to manufacturability of composite parts. Draping algorithms are incorporated in simulation software, available commercially, like MSC.Laminate Modeler [47] and Fibersim [48].

However, to this day it could not be found in the literature draping being considered in variation simulation analyses. Therefore, further research about the effect of the orientation variation caused by draping in the final geometry needs to be performed.

### 5.1.4 *Curing*

Sources of stress build-up and shape distortions during curing are discussed in [49]. It also presents experimental results that identify parameters that drive shape distortions. Analytical solutions for spring-in of curved composite parts are presented in [50, 51]. Curing simulation of a T-shaped profile, focused on geometry variation, is performed in [35, 42]. Similar analysis, for a C-shaped profile, using a two-step FEA procedure simulation, was performed in [39]. In [37, 41], different thicknesses, stacking sequences and tool radii are compared in curing simulation of L- and C-shaped profiles. Another paper that studies C-shaped profiles is [43]. Variation in thickness and spring-in in a L-shaped part are studied in [38, 52, 53]. A comparison of thin and thick angled composite shell structures is performed in [40], with good agreement between analytical and experimental results.

All research cited above involve shell laminates. For sandwich panels, an analytical model for the prediction of spring-in is shown in [54]. In [55], process induced deformations for a U-shaped sandwich panel are analyzed. However, further curing simulations for sandwich panels need to be developed.

### 5.2 Variation simulation for assemblies

Although there are many studies in variation simulation for composites, much more research was performed with metallic parts, and many of the tools and features can be applied to composite materials with no major modifications. A discussion about the applicability of the existing tools for assemblies with composite parts is presented below.

#### *5.2.1 Non-rigid parts*

In many simulation cases, all parts are assumed to be rigid. However, in automotive and aerospace industries, for example, non-rigid parts are common, both in metallic and composite materials, especially thin and large parts. Non-rigid parts, also known as compliant parts, can present variations due to deformations induced by gravity or forces generated during manufacturing.

Due to the anisotropic nature of composite materials, the way a composite part deforms is different from a metallic part. FEA is usually applied to compute compliant behavior. For thin laminates, parts can be modeled with shell or solid elements. In the former, only the global properties are calculated, using classical laminate theory, assuming the layers are perfectly bonded together, as in [4, 35, 56, 57]. In the latter, as in [36, 37, 39, 40, 43], each ply is modeled separately, also providing results for each ply.

For sandwich panels, shell and solid elements, or a combination of them, can be used for modeling, depending on the part geometry and desired results.

To avoid the necessity to run a FEA for every DMC simulation, the method of influence coefficient (MIC) can be used [58]. In this method, a linear relationship between part deviations and assembly deviations is calculated using FEA, resulting in a sensitivity matrix. Then, for each DMC iteration, this matrix is used to calculate deformations, instead of the finite element model. A review of the MIC was performed in [59] and applications of the method in composite assemblies can be found in [4, 60, 61].

#### *5.2.2 Contact modeling*

Due to geometric variations in parts and fixtures, parts may penetrate each other during simulation. To prevent that effect, contact modeling is used, generating forces in the parts caused by collisions between surfaces in contact. A methodology was described in [62], and a modification was proposed in [31].

The contact modeling methodology can be applied to composite materials with no further development, as in [4, 61], since it does not depend on the type of material of the parts, but rather on their surface shape.

#### *5.2.3 Locating Schemes*

During assembly, the parts to be joined are positioned using fixtures. The fixture is the physical representation of the locating scheme, that locks the six degrees of freedom of a part in space. As stated before, the positioning fixture is not free from deviations, transmitting them to the assembly, and can also amplify or attenuate the variations from each part of the assembly [6], depending on the geometry of the parts and positioning of the locking points. How sensitive to variation the fixture is will define the robustness of the locating scheme [63].

The locating scheme is independent of the type of material of the parts, so the current optimization methodologies, such as the one described in [29], can be used for composite materials with no further modifications.

#### *5.2.4 Clamping forces*

Clamping forces induce stresses and deform the parts, when they are not nominal, forcing them to the intended positions in the fixture. Tolerancing analyses of composite assemblies, considering clamping forces, were performed in an aircraft elevator assembly [64] and in a wingbox assembly [65].

Clamping forces modelling is similar for metallic and composite parts, so techniques developed for metallic assemblies will work for composite assemblies, too.

#### *5.2.5 Shimming and bonding*

In metallic welded assemblies, forces are applied to close the gap between the parts, avoiding the use of shims between parts. In composite assemblies, however, welding is not possible, so when rivets and bolts are used, the eventual gap is filled with shims (liquid, solid or laminated shims) to avoid pre-tension in the parts. The shim thickness and angle is limited by structural analysis and manufacturability, so it is important to control these parameters.

Numerical processes to predict the gap between parts in an assembly are described in [66–70]. In these methods, scanned data is used to predict the gap before assembly. This allows the shim manufacturing and installation without the non-added value and time-consuming processes of pre-assembly and gap measurement.

Nevertheless, these methods are applicable to the production phase, and it is important to have an estimation of the gap during the design phase, to check if it will be within established limits. Therefore, a statistical simulation process for shimming thicknesses and angles is necessary.

A similar problem is found in bonded joints. In such cases, the gap between parts define the adhesive thickness, which directly affects the bonding performance. Analyses of adherends misalignment and length on the performance of bonded joints are performed in [71–73].

Adhesive shrinkage after curing is a well-known phenomenon [74], and will induce forces that may cause geometric variations in the assembly, as seen in [35, 36, 42]. Especially when complex-shaped parts are bonded together, it is not obvious how the adhesive thickness will vary along the interface. Although a constant nominal gap is usually designed between the parts to accommodate the adhesive, variations in the parts and location points may lead to non-uniform adhesive thicknesses. Papers related to geometric variation caused by non-uniform adhesive thickness were not found in the literature and requires further research.

### *5.2.6 Joining sequence*

There are several studies about how the joining sequence of an assembly can be optimized to improve the geometric quality output, mostly related to spot welding sequence in the automotive industry, with metallic parts assemblies [75]. In [76], a rapid stepwise algorithm for optimization of the spot welding sequence related to the assembly geometric variation is proposed.

Approaches for fastener sequence installation optimization are proposed in [77, 78], by minimizing the residual gap after fastening.

A joining sequence optimization method could be developed for composite assemblies, with rivets and bolts as joining methods. Besides, the optimization of the installation sequence of temporary fasteners, focused in minimizing the shimming thickness or geometric variation could also be studied.

### *5.2.7 Selective assembly*

In selective assembly, parts are individually measured, sorted and matched before the assembly, improving the output quality. In [79], three sheetmetal assemblies were studied, leading to improvements of up to 53% in variation and mean deviation. This study was further developed in [80], by adding locator adjustments techniques.

For composite parts, a process for selective assembly, focused on geometric variation, stresses or shimming optimization, could be developed. As stated in [79], the drawback of using selective assembly is the need of measuring all produced parts with high accuracy and matching them before each assembly. For a high-volume and fast-paced industry, like the automotive, it may not be feasible to implement such techniques. Although, for a lower volume production, as in the aerospace industry, there could be more time to perform a selective assembly process. Besides, in some cases of large composite aircraft parts, all parts in a batch are already measured for quality assurance, so it would not be an extra task. The high cost of such parts could also be used to justify the use of this technique, since it would reduce the scrap rate by allowing more parts to be used.

## 6 FUTURE CHALLENGES

Advanced composite materials are still expensive and limited to high performance products. In order to expand their use, making the whole manufacturing process cheaper and predictable is beneficial. One way of achieving this is by reducing the scrap rate and rework due to geometric variations, that can affect a product quality or function. Therefore, a geometry assurance process for composites is needed.

Although several studies, as shown in this paper, were and are being developed for composites, the following research gaps were identified:

1. Most of variation simulation studies in composites are performed with the same layup and stacking sequence (see section 5.1.1) throughout the part. Variation simulation with different layups and stacking sequence in the same part needs further development, in order to study the effects of the layup transition, for example;
2. Few studies considering fiber orientation variation in variation simulation were found, as stated in section 5.1.2, so further studies are needed, with different geometries and layups;
3. Draping can change the layers' orientation in relation to the global coordinate system, as discussed in the section 5.1.3, leading to unforeseen variations after curing. Draping can be included in variation simulation studies to characterize the effect in the final geometry after curing;
4. Sandwich laminates require a different modeling strategy, sometimes combining shell and solid elements, to enable the analysis of core ramps and laminate transition. Curing simulation and variation simulation for sandwich laminates are not many and could be further explored (see section 5.1.4);
5. As discussed in 5.2.5, eventual gaps between parts in an assembly are filled with shims before joining. The thickness and angle of the shims are of great interest,

Journal of Computing and Information Science in Engineering. Received July 18, 2022;
Accepted manuscript posted February 21, 2023. doi:10.1115/1.4057021

since the performance of the joint is affected. Similarly, in bonded joints the thickness of the adhesive is of great interest, because it also impacts the joint performance. In this case, it is also important to understand how the variation in the adhesive thickness will geometrically affect the assembly, after curing and shrinkage of the adhesive. Therefore, shimming prediction and bonding layer shape prediction due to variations in parts and assemblies need further development.

6. Several studies with spot welding in sheetmetal assemblies were already performed regarding joining sequence optimization (see section 5.2.6). Riveting or bolting joining sequence optimization in composite parts is a similar problem, but needs more research, since there are differences in the manufacturing process. Moreover, installation sequence of temporary fasteners, focused on optimization of shimming or geometric variation needs further progress;
7. A selective assembly process for composite assemblies could be developed, based on existing studies for sheetmetal parts (see section 5.2.7). Besides geometric variation, further research in selective assembly could be performed focused on stresses and shimming optimization.

## 7 CONCLUSION

As a conclusion, after the literature review, this paper provides an overview of the state-of-art in the field of geometry assurance for composites and shows that there are many open challenges, mainly due to additional variables in the manufacturing process, when compared to metallic parts. By adding these variables to the simulations, variation simulation becomes closer to reality, increasing the predictability and improving the precision of predictions. Ultimately, this will increase the range of application of composite materials and also reduce the scrap rate during manufacturing. By pointing out these challenges, this paper provides a roadmap to follow in the field of geometry assurance for composites.

## ACKNOWLEDGEMENTS

This work was carried out at Wingquist Laboratory and the Area of Advance Production at Chalmers within the project “Resilient manufacturing of composites (RECO)”, financed by the strategic innovation program Produktion2030, supported by Vinnova. The support is gratefully acknowledged.

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