Thesis for The Degree of Licentiate of Engineering

Towards a Geometry Assurance Framework for Compliant Composite Assemblies

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"Tolerance is nothing more than patience with boundaries."
- Shannon L. Alder

Abstract

The increasing adoption of carbon fiber reinforced polymer (CFRP) composites in aerospace structures introduces geometric challenges that must be managed to ensure dimensional quality in production. During manufacturing, process-induced deformations such as spring-in and warpage cause composite parts to deviate from their nominal geometry, and these deviations are systematic rather than random, forming a design-specific manufacturing signature. When deviated parts are assembled, gaps form at the mating interfaces. Installing fasteners across open gaps induces forced-fit stresses, so gaps are filled with shims before fastening. Shimming, however, introduces its own structural penalty, increasing the bending stress carried by the fasteners as shim thickness grows. The interface between mating parts must therefore satisfy two competing requirements at once: post-assembly geometric quality and structural joint integrity.

This thesis develops simulation-based methods to support geometry assurance in shimmed compliant CFRP assemblies, with focus on managing this interface from both the assembly and the design stage. Two research questions are addressed. The first establishes the state of the art in geometry assurance for composites, identifying the variation sources and simulation challenges that distinguish composite assemblies from metallic ones. The second examines how interface management can balance geometric quality and joint integrity, from both the assembly and the design stage.

The work is based on three appended papers. In Paper A, a structured literature review maps the open challenges in geometry assurance for composites and shows that the systematic manufacturing signature, which has no counterpart in metallic variation simulation, propagates into the assembly as the interface gap that must be managed. In Paper B, using a CFRP wingbox section as a virtual case study, fixture adjustment is then shown to reduce interface gaps by 43% while respecting the structural shim limit, but this gap reduction increases post-assembly geometric deviation in the majority of cases, revealing a conflict between local gap minimization and global geometric accuracy. In Paper C, at the design stage, a non-monotonic relationship between the design gap and post-assembly deviation is identified, with an optimal gap of approximately 0.3 mm that minimizes deviation and remains consistent across manufacturing populations with different signatures, while larger gaps add shim thickness, and with it fastener loading, without geometric benefit.

Together, these results show that interface management can balance geometric quality and joint integrity through complementary levers at the design and assembly stages, quantified rather than left to engineering judgment, and lay the groundwork for integrating process-induced deformation predictions into assembly geometry assurance.

Keywords

geometry assurance, composite assembly, variation simulation, shimming, fixture optimization, design gap

List of Publications

This thesis is based on the following publications:

[**Paper A**] **D. Toyoda**, K. Wärmefjord, R. Söderberg, *Challenges in geometry assurance for composites manufacturing*
Journal of Computing and Information Science in Engineering 23(5) (Oct 2023), 051007-051013, DOI: 10.1115/1.4057021.

[**Paper B**] **D. Toyoda**, R. Sadeghi Tabar, L. Lindkvist, K. Wärmefjord, R. Söderberg, *Gap reduction vs. geometric deviation: a trade-off in composite assembly*
In press, Procedia CIRP (19th CIRP Conference on Computer-Aided Tolerancing - Edmonton, Canada).

[**Paper C**] **D. Toyoda**, L. Lindkvist, K. Wärmefjord, R. Söderberg, *Design gap specification in shimmed composite assemblies: trade-off between geometric deviation and shim thickness.*
Submitted to The International Journal of Advanced Manufacturing Technology, under review.

Distribution of Work

The distribution of the work for each paper is as follows:

Paper A. Toyoda, Wärmefjord, and Söderberg initiated the idea. Toyoda conducted the literature study and wrote the paper, with Wärmefjord and Söderberg acting as reviewers.

Paper B. Toyoda and Sadeghi Tabar initiated the idea and carried out the studies. Toyoda wrote the paper, with Sadeghi Tabar, Lindkvist, Wärmefjord and Söderberg acting as reviewers.

Paper C. Toyoda initiated the idea. Toyoda and Lindkvist carried out the studies. Toyoda wrote the paper, with Lindkvist, Wärmefjord and Söderberg acting as reviewers.

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Contents

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List of Acronyms

CAT	Computer-Aided Tolerancing
CFRP	Carbon Fiber Reinforced Polymer
CLT	Classical Laminate Theory
CTE	Coefficient of Thermal Expansion
DRM	Design Research Methodology
DS-I	Descriptive Study I
DS-II	Descriptive Study II
FEM	Finite Element Method
GA	Geometry Assurance
MIC	Method of Influence Coefficients
PID	Process-Induced Deformation
PS	Prescriptive Study
RC	Research Clarification
RMS	Root Mean Square
RQ	Research Question

Chapter 1

Introduction

In this chapter, the introduction to the research and the scope of this study are presented.

1.1 Background

Carbon Fiber Reinforced Polymer (CFRP) composites have been increasingly adopted as primary structural materials across high-performance industries, most prominently aerospace, driven by their exceptional strength-to-weight ratio, corrosion resistance, and fatigue performance [1], [2]. In aircraft structures such as wings and fuselages, replacing metallic components with CFRP reduces structural mass, directly improving fuel efficiency and reducing emissions [3], [4]. However, realizing these benefits in large-scale production requires managing the geometric challenges that are inherent to composite manufacturing.

Unlike metallic parts, whose geometry is largely determined by rigid tooling, machining, or forming operations, composite parts develop their shape through a coupled sequence of draping, curing, and trimming [5], [6], making the resulting deviations systematic and design-specific. During curing, mismatches in the Coefficient of Thermal Expansion (CTE) between fibers and resin generate residual stresses that are released upon demolding, producing characteristic shape distortions known as spring-in and warpage [7], [8], [9], [10], [11]. These Process-Induced Deformations (PIDs) cause the as-manufactured geometry to deviate from the nominal design and, since they are influenced by part geometry, layup, and process conditions, they cannot be entirely eliminated [12], [13], [14], [15].

When geometrically deviated parts are brought together in an assembly, these deviations produce gaps at the mating interfaces between parts. In CFRP structures, installing fasteners across an open gap forces the parts into contact, inducing stresses that can cause delamination and matrix cracking [16]. The standard industry practice to prevent this is shimming, where thin layers of solid or liquid material are inserted at the interfaces before fastening [17]. While shimming eliminates forced-fit damage, it introduces its own challenges: the shim modifies the load path through the joint and increases bending stresses in the fastener, with the magnitude of this effect growing with shim thickness. There is therefore a structural limit on how much shimming is acceptable, which depends on the fastener geometry, the joint dimensions, and an allowable-stress margin introduced in Section 2.6. The acceptable shim thickness is therefore bounded by structural considerations rather than geometric ones. How geometric variation itself is managed across the development process is the subject of Geometry Assurance (GA).

1.2 Geometry assurance

GA encompasses all activities aimed at minimizing the effect of geometric variation on the final product, across all phases of the development process [18]. As illustrated in Figure 1.1, these activities are performed across three phases of product realization. In the concept phase, variation simulation, joining simulation, and robust locator design are used to evaluate candidate concepts and locating schemes, so that designs with low sensitivity to variation are established early. In the verification phase, fixture optimization and inspection preparation refine the detailed design and prepare the measurement of physical parts before production begins. In the production phase, inspection, statistical process control, and root cause analysis are used to monitor and maintain geometric quality, closing the loop back to design [18].

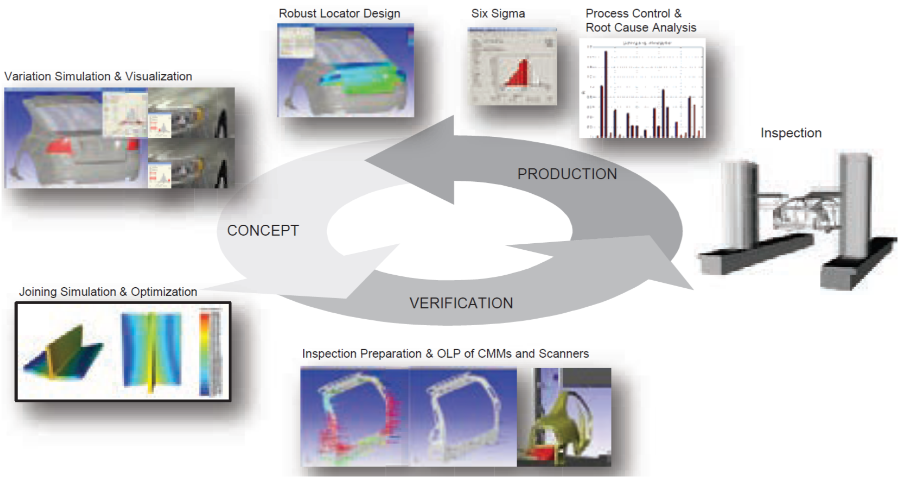

Figure 1.1: Geometry assurance activities across the product realization process [18].

In the automotive and aerospace industries, variation simulation tools are routinely used to predict how part-level deviations propagate through assemblies, enabling virtual evaluation of design alternatives before physical production begins. For metallic assemblies, these methods are well established. For composite structures, however, the additional variation sources introduced by the manufacturing process, combined with the compliant behavior of thin-walled parts during assembly, pose challenges that existing tools and methods have not fully addressed [19]. Closing this gap for composite assemblies is the motivation for the present work.

One tool available to improve dimensional outcomes in assembly is locator adjustment, where the positions of the fixture locators are optimized to reduce interface gaps and improve part alignment [20]. By computing the optimal adjustment based on measured part geometry, it is possible to reduce shimming needs before fastening. In a digital twin context, inspection data from individual parts can feed directly into this optimization, enabling pre-manufactured shims to be prepared in advance and reducing in-process rework. However, adjusting locators to minimize gaps displaces the assembly from its nominal geometry, and the geometric consequences of this trade-off are not well understood for compliant composite structures.

A complementary challenge arises at the design stage. A design gap can be prescribed in the nominal CAD geometry, introducing an intentional interface clearance between mating surfaces to accommodate manufacturing deviations and reduce contact forces during fixturing. When present, the magnitude of this gap significantly influences both the shimming required and the post-assembly geometric accuracy. However, whether to include a design gap and at what value to specify it are decisions that currently lack formal simulation-based guidance, relying instead on engineering judgment and accumulated experience.

1.3 Research purpose and questions

The challenges described above motivate the aim of this thesis: to develop simulation-based methods that support geometry assurance in CFRP assemblies, with focus on understanding the trade-offs between interface gap management, structural constraints, and post-assembly geometric quality. Two Research Questions (RQs) are investigated:

RQ1: What are the current main challenges in geometry assurance for composite parts and assemblies?

This question is framed to establish the state of the art in GA for composites, identifying the variation sources specific to composite manufacturing and assessing to what extent existing simulation tools, developed primarily for metallic structures, are applicable. The answer provides the foundation and motivation for RQ2.

RQ2: How can interface management balance geometric quality and joint integrity in compliant composite assemblies?

This question addresses the tension between maintaining the dimensional quality of the assembled product and preserving the structural integrity of its joints. In composite assemblies these objectives can conflict, because the interface between parts must absorb manufacturing variation while serving as both the geometric datum and the load path of the joint. This balance is examined from two complementary directions: the management of interface gaps during assembly, and the specification of the design gap at the design stage.

1.4 Delimitations

This thesis focuses on GA in the assembly of shimmed CFRP structures, specifically on the management of interface gaps through fixture adjustment and design gap specification.

The studies presented are based on virtual case studies using numerically generated part populations, and no physical experiments or measurements on manufactured parts are included. The manufacturing signature of the part populations in Paper C is prescribed numerically, informed by the characteristic spring-in deformation predicted by curing simulations, rather than obtained from a process simulation of the specific parts. The curing and draping processes that produce PID are not themselves investigated; the prescribed signature serves only to generate representative deviated geometries. This is sufficient for the purpose of Paper C, because the assembly response to the design gap is governed by the geometry of the deviated parts entering assembly, not by the process that produced that geometry. The variation simulation operates on the deviation field itself, so two parts with the same systematic deviation respond identically regardless of their manufacturing history. To ensure the findings do not depend on a single assumed signature, the study evaluates two populations with contrasting characteristics, one with a consistent spring-in bias and one without a dominant signature, and the design-gap behavior is examined across both. Incorporating process simulation of these manufacturing steps as a predictive input to assembly variation simulation is a natural extension of this work but is not addressed here.

The structural analysis of shimmed joints is limited to single-shear fastener configurations under static shear loading. Dynamic loads, fatigue, and multi-fastener load redistribution effects are not considered. The shim thickness limits derived in Paper B are based on analytical beam theory and are intended as conservative guidelines rather than a full structural certification analysis.

Finally, the results are demonstrated on a simplified wingbox section representative of aerospace primary structures. While the methods are general in principle, their applicability to other assembly configurations or industries has not been demonstrated.

1.5 Outline of the thesis

This thesis consists of six chapters. Chapter 1 introduces the industrial and research context, identifies the gaps that motivate the work, and states the research aim, questions, and delimitations. Chapter 2 presents the frame of reference, establishing the theoretical foundation for the research. Chapter 3 describes the research methodology and the methods employed. Chapter 4 presents the results of the three appended papers. Chapter 5 discusses the results in relation to the research questions, states the scientific and industrial contributions, evaluates the verification and validation of the developed supports, and identifies directions for future work. Chapter 6 states the conclusions of the thesis.

Chapter 2

Frame of Reference

This chapter presents the theoretical foundation underpinning the research, establishing the key concepts relevant to GA in composite assemblies. The chapter is structured to build progressively from the material and manufacturing context, through the GA framework and simulation tools, to the specific assembly challenges addressed in the appended papers.

2.1 Composite materials and manufacturing

A composite material combines two or more constituents to achieve properties superior to those of the individual components, while each constituent retains its own chemical and physical identity [21]. In high-performance applications, advanced composites are used: high-strength reinforcing fibers embedded in a polymeric matrix (or resin) to form a ply, with several plies stacked at different orientations to build a laminate [22]. In the aerospace industry, CFRP is the dominant material owing to its high specific strength and stiffness and its favorable fatigue and corrosion behavior [23].

Because the fibers carry load preferentially along their direction, a laminate is anisotropic, and its stiffness and strength can be tailored to the expected load path by selecting the orientation and sequence of the plies [24], as illustrated in Figure 2.1. This tailorability is a central design advantage of composites, but it also makes their mechanical response, and hence their deformation during manufacturing and assembly, more difficult to predict than that of an isotropic metal. The laminates considered in this thesis use bidirectional woven fabric, in which each ply carries fibers in two orthogonal directions, so a single fabric ply is denoted by a pair such as (0/90) or (±45). Where greater bending stiffness is required at low weight, two laminate skins may be separated by a lightweight core to form a sandwich structure [21], although the assemblies considered in this thesis are monolithic laminates.

The material properties used in the variation simulations of this thesis are obtained in two steps: the constituent fiber and resin properties are first combined into orthotropic single-ply properties using the rule of mixtures under iso-strain (Voigt) assumptions, and Classical Laminate Theory (CLT) is then

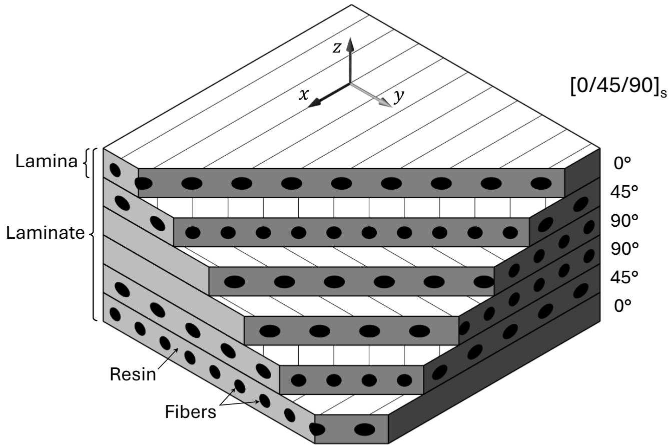

Figure 2.1: Construction of a laminate from unidirectional plies stacked at different fiber orientations, for a symmetric ($[0/45/90]_s$) sequence. Adapted from [25].

applied to the orientations and stacking sequence of each part to obtain the effective laminate stiffness [22].

While CLT provides the stiffness of the laminate, the acceptability of a stress state in an anisotropic material requires a dedicated failure criterion, since strength differs along and across the fiber direction. The Tsai-Hill criterion combines the in-plane stress components, normalized by the corresponding strengths of the ply, into a single scalar value, with values approaching one indicating the onset of failure [24]. In this thesis, Tsai-Hill values computed from the variation simulation are used in Paper B to quantify the structural loading induced in the laminates during assembly.

The manufacture of an advanced composite part typically proceeds through a sequence of steps: cutting the plies, laying them up over a mold in the prescribed orientations, infusing resin where pre-impregnated material is not used, compacting the stack, curing, and finally machining the edges, holes, and cut-outs, as illustrated in Figure 2.2. Layup may be performed manually or by automated fiber placement and automated tape layup, which deposit pre-impregnated tows and strips directly onto the mold with higher repeatability than manual layup [23]; laser projection of the ply contours onto the mold is sometimes used to aid manual placement [26]. When dry fibers are used, resin is introduced in a separate step such as resin transfer molding [27]. Compaction, commonly achieved with a vacuum bag, consolidates the plies and removes excess resin and entrapped air [28]. Curing may take place at room temperature, in an oven, or in an autoclave, the latter additionally applying pressure to improve consolidation of the plies into a solid laminate [29].

Unlike sheet metal structures, composite parts cannot be joined by welding. The most common joining methods for composite assemblies are mechanical fastening with rivets, pins/collars or bolts and adhesive bonding [30]. Riveted

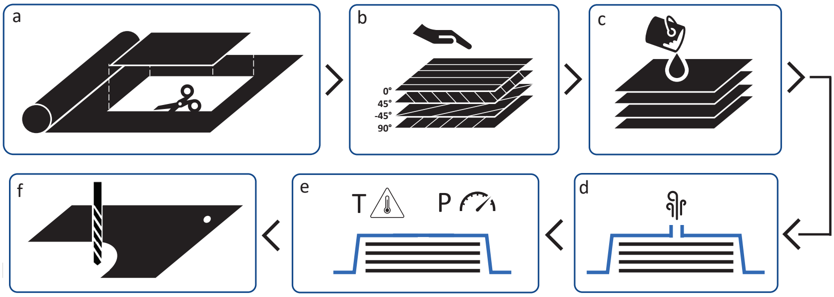

Figure 2.2: Manufacturing steps: (a) cutting, (b) placing, (c) infusing the resin, (d) compacting, (e) curing and (f) machining [19].

joints are typically pre-drilled, with temporary fasteners used to align the holes and apply small forces that close minor gaps before final fastening [31]. Bolted joints are preferred for highly loaded connections and for removable components such as access panels and control surfaces. Adhesive joining may be achieved through secondary bonding of two cured parts, co-curing of two uncured parts, or co-bonding of a cured part to an uncured one [30]. Interface gaps between mating parts cannot be closed by forcing the parts into contact, as is common in sheet metal assembly, since this would risk the forced-fit damage discussed in Chapter 1, nor is there welding to hold them in that position. Such gaps must instead be filled with shims prior to fastening, a practice central to the present work and addressed in Section 2.5.

Every step in this process chain is a potential source of geometric variation, and composite manufacturing is generally more variation-prone than the machining or forming of metal parts, particularly where steps are performed manually [32]. A comprehensive treatment of the variation sources associated with each manufacturing step is given in Paper A; Section 2.2 focuses on those most relevant to the geometric quality of the assembled product.

2.2 Geometric variation in composite parts

Geometric variation is inherent to every manufacturing process, and a deviation becomes a defect only when it falls outside the acceptable range defined by the tolerance [32]. While variation can arise at any of the manufacturing steps described in Section 2.1, a large and characteristic part of the final shape deviation of a composite part is established during curing, when the part transforms from a pliable layup into a consolidated solid [32]. The present section focuses on this PID, since it dominates the part-level geometry that subsequently propagates through the assembly.

During curing, internal stresses develop as the resin cross-links and shrinks, and these stresses, combined with the anisotropy of the laminate, relax into a change of shape once the part is removed from the mold [33].

For curved or angled features, the most prominent manifestation is spring-in, the reduction of an enclosed angle relative to its nominal value, while a nominally flat region may exhibit warpage, a departure from flatness [34], as illustrated in Figure 2.3. These distortions arise from several mechanisms. Spring-in is driven primarily by the anisotropy of thermal and cure shrinkage, which differs through the thickness and around a corner, contracting the enclosed angle on demolding [35]. Warpage in nominally flat regions arises from through-thickness asymmetry, such as a gradient in fiber volume fraction, where plies nearer the tool consolidate differently from those further away; because local thermal expansion depends on fiber content, the resulting asymmetry produces a departure from flatness even in otherwise flat parts [36]. Tool-part interaction, in which the CTE mismatch between part and mold induces shear stresses at the interface during the thermal cycle, contributes to both [35]. Both spring-in and warpage have been studied extensively through experiment and simulation for representative coupon geometries such as L- and U-shaped profiles [37], [38], [39].

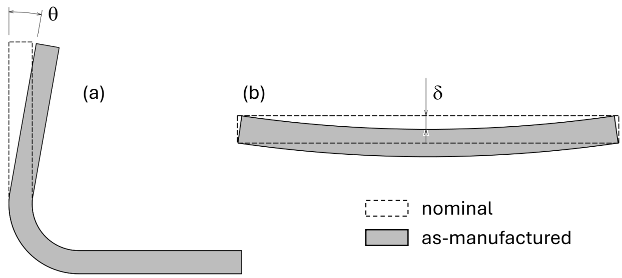

Figure 2.3: Characteristic process-induced deformation of composite parts: (a) spring-in, measured by the angle θ, and (b) warpage, measured by the maximum deflection δ.

The magnitude of PID can be reduced through laminate design. A balanced laminate pairs each off-axis ply with one of opposite orientation, a symmetric laminate mirrors the stacking sequence about the mid-plane, and a quasi-isotropic layup distributes orientations so that in-plane properties are nearly direction-independent; these measures limit the asymmetries that drive distortion [40]. However,such design rules reduce but do not eliminate the deformation, and a residual, systematic shape change remains for a given part design and process [41]. This residual deformation is repeatable: nominally identical parts produced under the same conditions tend to deform in the same characteristic way, distinct from the random, part-to-part scatter superimposed upon it.

This distinction between systematic and random deviation is central to how part variability is represented in geometry assurance. The repeatable component can be described as a characteristic mean shape, sometimes termed the manufacturing signature, which captures the deformation a particular part design is expected to exhibit [42]. For variation studies conducted before physical parts exist, this signature can be obtained from a curing simulation of the part and then combined with random nodal perturbations to generate a representative population of deviated geometries, each differing in its individual scatter but sharing the common signature [43]. The directional bias of this signature can have a decisive effect on assembly outcomes, since two populations with identical random spread but different signatures may respond differently to the same design decision; this influence is investigated in Paper C.

A curing simulation predicts the signature by modeling the thermomechanical development of residual stresses through the cure cycle, as the resin solidifies and the constrained laminate is then released from the mold, giving the as-cured shape of the part [44]. The fidelity of such a prediction depends on the local fiber orientations, since these govern the anisotropic stiffness and thermal response that drive the deformation, and these orientations are in turn determined by how the plies drape over the mold. The prediction of PID therefore rests on a chain that runs from draping, through the resulting fiber orientations, to the curing analysis that yields the signature. In this thesis the signature is prescribed rather than computed through process simulation, as set out in the delimitations; predicting it this way is returned to as a direction for future work.

The way such part deviations propagate through the assembly, once the parts are positioned, clamped, and joined, is the subject of the variation simulation methods described in Section 2.4.2.

2.3 Robust design

A design whose geometric output is insensitive to the variation of its inputs is termed a robust design, and achieving such insensitivity is a central objective in the assembly of compliant structures. The concept originates in the quality engineering of Taguchi [45], which distinguishes between control factors, the parameters a designer can specify and manipulate, noise factors, the sources of variation that cannot be practically controlled, and signal factors, the inputs set by the user to obtain a desired value of the response. This system view of a product or process, acted on by these factors and producing a measurable response, is illustrated in Figure 2.4. Here the noise factors are the geometric deviations of the incoming parts, and the response is the geometric quality of the assembled product; the control factors available to influence it are introduced in the following paragraphs.

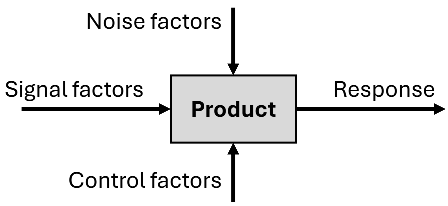

Figure 2.4: The robust design system view, in which a product or process is acted on by controllable design factors and uncontrollable noise factors to produce a measurable response [46].

A sensitive concept amplifies the effect of noise factors on the product's response, whereas a robust concept absorbs the same variation with a smaller effect on the final geometry. Because tightening tolerances to compensate for a sensitive concept raises manufacturing cost steeply, it is generally preferable to reduce sensitivity through the choice of control factors in the early design phase, accepting wider tolerances at lower cost [47]. The aim is thus not to remove variation, which is impossible, but to configure the product and its assembly so that the unavoidable variation has as little effect as possible on the characteristics that matter.

Robust design is classically pursued through three stages: system design, in which the basic concept and architecture are selected; parameter design, in which the nominal values of the control factors are chosen to minimize sensitivity to noise; and tolerance design, in which tolerances are allocated by trading the resulting quality loss against manufacturing cost [45], [46]. The dominant focus of the approach is parameter design, and the work in this thesis operates at this level: rather than allocating tolerances, it treats the fixture adjustment of Paper B and the design gap of Paper C as control-factor settings whose values determine how robustly part variation is accommodated during shimmed assembly.

In the geometric context, the principal control factor is the locating scheme, which positions and constrains a part during manufacturing, assembly, and inspection [48]. Its placement strongly governs robustness, and the locating scheme and its active adjustment are treated in Section 2.4.1. The model-based methods by which robustness is pursued for geometric variation specifically, from the early evaluation of concepts to the control of variation in production, are together known as geometry assurance, described in the following section.

2.4 Geometry assurance

Geometry assurance provides the methods and activities through which robust geometric design is achieved in practice. It is the field concerned with the simulation, analysis, and control of geometric variation throughout the product lifecycle, from the manufacturing of individual parts to the final assembled product, with the aim of delivering the geometric quality required for function, aesthetics, and downstream assembly [18], [47]. Since geometric variation cannot be eliminated, the objective is to ensure that its effect on the final product remains within acceptable limits at the lowest possible cost.

Geometry assurance activities are commonly organized across three phases of product realization: a concept and design phase, in which the product and its assembly are made robust against variation; a verification and pre-production phase, in which the chosen concept is evaluated and inspection is prepared; and a production phase, in which variation is monitored and controlled during manufacturing [18], as shown in Figure 1.1.

A set of model-based tools supports these activities across the phases, together referred to as the virtual geometry assurance toolbox, spanning variation simulation, locator and fixture design, tolerance analysis, and inspection preparation [18]. The robustness of a concept is evaluated within this toolbox through a sequence of analyses. Stability analysis disturbs the locating points and propagates the response through the part, identifying the regions most sensitive to positioning variation so that the scheme can be improved before tolerances are set. Variation analysis then simulates the effect of the allocated tolerances on critical measures, typically by Monte Carlo simulation, in which many assemblies are sampled from the tolerance distributions to build a statistical picture of the resulting variation, to verify that it stays within the specified limits. Where it does not, contribution analysis ranks the individual tolerances by their effect on a given measure, indicating where tightening would be most effective. Together these analyses make robustness a quantitative property that can be assessed virtually, before any physical part is produced.

Increasingly, however, geometry assurance is moving toward an individualized treatment, in which inspection data from each manufactured part inform the assembly of that specific unit, enabling adaptive control rather than fixed settings. This individualized approach is realized through the digital twin, in which a virtual model of the product and its process is continuously updated with measurement data from production and, in turn, feeds decisions back to the shop floor to act on each individual unit; the concept and the realization concepts that build upon it are discussed in Section 2.8. Two of the methods on which these activities depend, the locating scheme that constrains each part and the variation simulation that predicts how its deviations propagate, are treated in the following subsections.

2.4.1 Locating schemes and locator adjustment

As introduced in Section 2.3, the locating scheme is the principal control factor governing the geometric robustness of an assembly. It is the arrangement of points and directions that positions and constrains a part during manufacturing, assembly, and inspection, realized in practice by the contact points of an assembly fixture. A rigid part has six degrees of freedom, and the classical 3-2-1 locating scheme fully constrains them through contact at three, two, and one points on mutually perpendicular planes, as illustrated in Figure 2.5. Compliant thin-walled parts, however, deform under gravity and the contact and clamping loads applied during assembly, and generally require additional support points to prevent unintended deformation, leading to an extended N-2-1 scheme with N greater than three [49].

While the locating scheme defines the nominal positions at which a part is held, these positions can also be used actively to improve the geometric outcome of the assembly. Locator adjustment, also referred to as fixture adjustment, is a geometry assurance technique in which the positions of the fixture locators are modified by small, controlled amounts to improve the dimensional quality of the assembled product [50], [51]. The technique presupposes an adjustable, or reconfigurable, fixture whose locator positions can be set per assembly rather than fixed. By optimizing these adjustments with respect to a geometric objective, it is possible to reduce interface gaps and improve part alignment, accommodating the specific deviations of the parts being assembled. When inspection data are available for the incoming parts, the adjustments can be

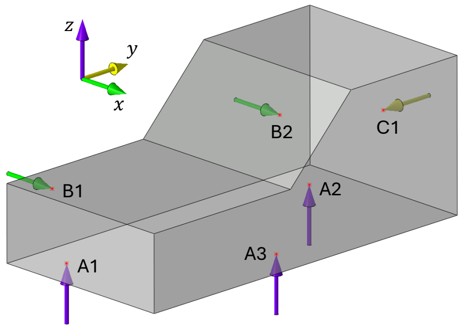

Figure 2.5: An orthogonal 3-2-1 positioning system. Adapted from [47].

tailored to each individual assembly rather than applied as a single fixed setting, an approach that has been demonstrated for individualized locator adjustment in a digital twin context [51].

In the assembly of shimmed composite structures, reducing the interface gaps through locator adjustment lowers the shim demand, since shim thickness is determined by the gap remaining after clamping, and thereby limits the adverse mechanical effects that thick shims introduce into the joint. The available adjustment is bounded, however: the displacement of each fixture point is restricted to a small range set by the fixture travel and common industrial shimming practice, and the resulting shims must remain within the maximum thickness permitted by the structural limits of the fasteners. Locator adjustment for gap reduction is therefore formulated as a constrained optimization problem, seeking the largest gap reduction that the fixture range and the structural shim limits allow. The derivation of this structural limit, and the formulation of the resulting constrained optimization problem as applied in Paper B, are presented in Section 2.6.

2.4.2 Variation simulation for compliant assemblies

For thin, large parts such as composite aerospace structures, the rigid-body assumption used in classical tolerance analysis is insufficient. These compliant parts deform under the clamping forces applied during assembly, and their final geometry depends on the interaction between part deviations, fixture constraints, contact forces, and fastening sequence. Non-rigid variation simulation accounts for this behavior, using the Finite Element Method (FEM) to model part deformation [52], [53].

The assembly of compliant parts is simulated as a sequence of steps that mirrors the physical process [53], [54]. The deviated parts are first positioned in the fixture against the locating scheme, establishing their initial location. Clamps and the contact between mating surfaces then bring the parts together, deforming them elastically and generating the contact forces that close or reduce the interface gaps. The parts are joined in this clamped state, the fasteners fixing the relative positions of the mating surfaces. Finally, the clamps are released and the assembly springs back as the locked-in elastic stresses partially relax, settling into the geometry that determines the final deviation of the released product. Each step contributes to the assembled result, and because the springback depends on where and in what order the parts are constrained and joined, the final geometry cannot be inferred from the part deviations alone but must be obtained by simulating the full sequence.

To avoid running a full FEM analysis for every Monte Carlo iteration, the Method of Influence Coefficients (MIC) is employed [52], [53]. In this approach, a sensitivity matrix relating nodal displacements to applied forces is pre-computed using FEM, linearizing the relationship between part deviations and assembly response. This matrix is then reused efficiently across hundreds or even thousands of simulation instances, enabling statistically robust variation analysis at manageable computational cost. The linearization assumes small displacements and elastic material behavior, which holds because the part deviations considered here remain small relative to the part dimensions, keeping the response within the linear-elastic regime of the laminates. Commercial Computer-Aided Tolerancing (CAT) software tools such as RD&T implement this combination of MIC and contact modeling for compliant assemblies.

Contact modeling is incorporated to prevent the mating surfaces from interpenetrating during simulation and to compute the contact forces arising from geometric mismatches, including the springback that occurs when the assembly is released from the fixture after joining [54]. Within the simulation, the interface clearance is governed by a contact detection distance, the separation at which two surfaces are treated as being in contact. By prescribing this distance relative to the nominal separation between the part mid-surfaces, a design gap can be introduced numerically, without redesigning and remeshing the parts for each configuration. The same mechanism represents shimming: once the gap remaining after clamping is determined, adjusting the contact detection distance to match it fills the gap numerically, so that fasteners are installed without inducing forced-fit stresses, reproducing the role of a physical shim. This numerical treatment of gaps and shims is the basis of the methods in Papers B and C.

This modeling approach relies on several simplifications. Contact between mating parts is modeled without friction, and surface roughness is neglected, as its magnitude is small relative to the geometric deviations of interest.

Fasteners are represented as rigid beam elements that constrain the connected nodes, and the shim is treated as a purely geometric gap-fill without mechanical stiffness. These are standard simplifications in non-rigid variation simulation, where the focus is the global deformation of the parts rather than the local behavior of the joint. Consequently, fastener flexibility, hole clearance, shim stiffness, and local stress concentrations are not captured within the assembly simulation; the structural effect of shim thickness is instead assessed separately through the analytical limit derived in Section 2.6 and applied in Paper B.

The geometric outcome of a variation simulation study is typically characterized using the Root Mean Square (RMS) of nodal deviations across the assembly, defined as:

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2} \tag{2.1}$$

where d_i is the deviation at node i and n is the total number of nodes. The RMS provides a single scalar measure that aggregates the spatial distribution of deviations across the entire assembly, making it suitable for comparing geometric outcomes across different assembly configurations or populations. In Papers B and C, RMS deviation is used both to characterize interface gap distributions and to evaluate post-assembly geometric accuracy across simulated part populations.

2.5 Interface gaps and shimming

When two compliant parts are brought together in an assembly fixture, their geometric deviations, together with the constraints imposed by the fixture, generally prevent the mating surfaces from meeting perfectly, leaving an interface gap between them. As noted in Section 2.1, such gaps cannot be closed by forming or forced contact as in sheet metal assembly: forcing deviated composite parts together to eliminate a gap induces residual stresses that can cause delamination and matrix cracking, and these forced-fit loads also reduce the margin available for operational loads [16]. To avoid introducing such stresses, the standard practice in composite assembly is to fill the interface gap with a shim before the fasteners are installed [30].

In this thesis, shimming refers specifically to the filling of an interface gap with solid or liquid material, and not to the adjustment of locator positions, which is sometimes also termed shimming [55] or trimming [56]. Solid shims are pre-formed inserts, often peelable laminated shims whose thickness can be adjusted on site by removing layers, while liquid shims are curable pastes that conform to the gap geometry and are well suited to irregular or variable clearances. In practice, a combination may be used, with a liquid shim accommodating the residual profile over a solid base. The choice and thickness of the shim follow directly from the measured gap, so that the gap distribution at the interface determines the shimming requirement of the joint.

Conventionally, the shim is determined by physical fit-up. Each component is positioned and clamped in the assembly fixture, the resulting interface gap is measured, for example with feeler gauges, and the assembly is then disassembled so that shims can be manufactured or selected to match the measured gap; the parts are finally reassembled and fastened [57]. This sequence is reliable but costly, requiring the assembly to be built, measured, taken apart, and rebuilt, and it places the shim preparation on the critical path of the assembly. There is therefore strong interest in predicting the gap, and hence the shim, before the parts are physically brought together, so that shims can be prepared in advance and the measurement and disassembly steps reduced [58], [59], [60].

Because the gap originates in part variation, it is not a single deterministic value but a quantity that varies from one assembly to the next across a production run, and its distribution can be predicted using the non-rigid variation simulation described in Section 2.4.2. This predictive view exposes a tension at the heart of shimmed composite assembly. Filling the gap prevents forced-fit stresses, but a thick shim modifies the load path and increases the bending stress carried by the fasteners, so the shim thickness cannot grow without limit; this structural limit is the subject of Section 2.6. At the same time, attempting to reduce the gap before fastening, for instance by adjusting the fixture as in Section 2.4.1, displaces the parts from their nominal positions and can degrade the geometry of the released assembly. The gap, the shim thickness, the joint integrity, and the final geometric accuracy are thus interdependent, and managing their relationship is the central concern of Papers B and C.

2.6 Fastener stress limits and constrained fixture adjustment

Section 2.5 established that interface gaps in composite assemblies are filled with shims to avoid the forced-fit stresses that would otherwise damage the joint. Shimming, however, introduces a structural challenge of its own. Mechanically fastened composite joints are commonly arranged in single or double shear, according to how many interfaces transfer the load. In a single-shear joint, two parts overlap and the load is carried across a single interface, so that the fastener is loaded eccentrically and experiences both shear and bending [61]. The bending moment arm in this idealized configuration is set by the thicknesses of the joined parts, the fastener being loaded in shear at the mid-plane of each part. Inserting a shim at the interface increases the separation between the load paths and therefore lengthens this moment arm, raising the bending stress carried by the fastener; the thicker the shim, the greater this effect.

Several approaches exist in the literature for defining acceptable shim thickness limits, ranging from empirical rules of thumb [61] to analytical derivations based on joint mechanics [62]. In Paper B, the limit is derived analytically for a single-shear joint configuration based on classical beam theory. Starting from the bending and shear stresses in the unshimmed fastener, the additional bending introduced by the shim is combined into a von Mises equivalent stress, and solving for the shim thickness at the maximum allowable stress yields:

$$t_s^{\max} = 2e_0 \left(\sqrt{k^2 + (k^2 - 1)\,\frac{3}{64}\,\frac{d^2}{e_0^2}} - 1 \right) \tag{2.2}$$

where $e_0 = (t_1 + t_2)/2$ is the bending moment arm, t_1 and t_2 are the thicknesses of the joined parts, d is the fastener diameter, and $k = 1 + f$ is a factor limiting the allowable increase in von Mises stress. The margin f is a design choice: in Paper B a value of $f = 0.15$ is adopted, limiting the shim-induced von Mises stress increase to 15% above the unshimmed value to retain sufficient margin for in-service loads, and it can be replaced by a certification-specified value without changing the derivation. For a given margin, the limit then depends only on the part thicknesses and the fastener geometry, making it straightforward to evaluate for any joint in the assembly.

This maximum allowable shim thickness is the limit beyond which shim thickness, and hence interface gap, cannot be tolerated without compromising joint integrity. It provides the structural bound referenced in the preceding sections and enters the locator adjustment introduced in Section 2.4.1 as a constraint. In Paper B, the adjustment is formulated as a constrained minimization problem:

$$\min_{u} \tau_\mu(u) \quad \text{s.t.} \quad \alpha \leq u_i \leq \beta, \quad t_s(u) \leq t_s^{\max} \tag{2.3}$$

where $\tau_\mu(u)$ is the RMS of interface gaps at fastener positions, u is the vector of locator adjustments, α and β are the lower and upper adjustment bounds, and the constraint $t_s(u) \leq t_s^{\max}$ ensures that the resulting shim thickness does not exceed the structural limit of Eq. 2.2. Because each evaluation of the gap field requires a call to the variation simulation, the objective is not available in closed form, and the problem is treated as a constrained black-box optimization. The gap field is approximated locally by finite differences, and the problem is solved with a trust-region reflective algorithm [63], which proceeds in two steps: an unconstrained penalty formulation that first enforces the adjustment bounds, followed by a quadratic surrogate that incorporates the maximum shim-thickness constraint. This formulation is the basis of the fixture-adjustment method developed in Paper B, where it is used to reduce shim requirements while observing the structural limits of the joint.

2.7 Design gaps

A design gap, also referred to as an intentional gap, nominal gap, or nominal clearance, is an interface clearance deliberately incorporated into the nominal CAD geometry between mating surfaces. It is a deterministic design parameter, applied uniformly across all assemblies of a given design, in contrast to the part-specific gaps that arise from manufacturing deviation. At fit-up, the total gap the shim must fill is the combination of the two: the prescribed design gap plus the manufacturing deviation of the particular parts. Its purpose is to accommodate the manufacturing deviations of the incoming parts, reducing the contact forces and fixture-induced deformation that arise when deviated parts are forced into contact during fixturing.

The specification of the design gap presents a paradox, as the two requirements it must satisfy pull in opposite directions. If the design gap is specified too small, part tolerances and fixture constraints generate contact forces that deform the parts during clamping, producing larger geometric deviations once the assembly is released from the fixture. If it is specified too large, the interface gap to be filled grows, increasing shim thickness, which adds weight and, as shown in Section 2.6, raises the bending stress carried by the fasteners. The design gap therefore governs both the geometric quality and the structural integrity of the assembled joint, and its specification cannot be optimized for one without consequences for the other.

Design-level solutions to avoid shimming altogether exist, such as splitting parts at the interface to create an overlap, as illustrated in Figure 2.6. However, these incur weight penalties and increase assembly complexity. The single-part architecture with shimming is therefore commonly preferred in aerospace practice, making the appropriate specification of the design gap a critical design decision.

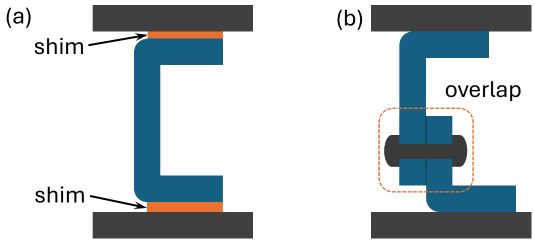

Figure 2.6: Two approaches to interface management: (a) single-part interface with a design gap filled by shimming; (b) split-part solution with an overlap that avoids shimming.

Despite its importance, the specification of design gaps in composite aerospace assemblies has historically relied on engineering judgment and accumulated experience rather than formal analysis. There is limited quantitative understanding of how the design gap interacts with manufacturing variability to affect the shim thickness distribution and post-assembly geometric deviation across a population of parts. Because the design gap is applied uniformly while the manufacturing deviation varies from part to part, its effect cannot be assessed on a single deterministic assembly but only statistically, over a representative population.

In simulation, a design gap can be introduced either by explicitly modifying the nominal part geometry to incorporate the clearance, or numerically by adjusting the contact detection distance in the variation simulation software without changing the part geometry, as described in Section 2.4.2. The latter approach avoids the computational overhead of geometry regeneration and is particularly suited to parametric studies where many gap values need to be evaluated. This is the basis of Paper C, which treats the design gap as an explicit design variable and sweeps it across populations of virtual assemblies to characterize its effect on post-assembly geometric deviation and shim thickness.

2.8 Digital twin

The digital twin concept represents an advanced application of GA principles, in which a virtual model of a product and its manufacturing process is kept synchronized with the physical system through a two-way exchange of data: measurements from production update the virtual model, and the model in turn returns decisions that act on the physical process [64]. This return path is what distinguishes a digital twin from a digital shadow, in which data flow only from the physical to the virtual side [65]. In a GA digital twin, inspection data from individual parts feed into variation simulation models, which return optimal fixture settings and predicted shim requirements to the assembly process, enabling adaptive decision-making for each individual unit. For composite assemblies, this could reduce pre-assembly measurement steps and rework. Both Papers B and C are motivated by a digital twin context, where the proposed simulation methods could operate on actual part inspection data to inform fixture setup and shim preparation before assembly begins.

Chapter 3

Research Methodology

This chapter presents the research approach employed in this thesis to address the challenges of GA for composite structures, its appropriateness for this research, and outlines the specific methods employed.

3.1 Research approach

This research aims to develop simulation-based methods that support GA in composite assemblies. The work is problem-oriented, starting from identified gaps in industrial practice and progressing toward methods that can be validated and adopted. This dual focus on understanding current limitations and prescribing solutions is characteristic of engineering design research, and positions the work within the Design Research Methodology (DRM) framework developed by Blessing and Chakrabarti [66], which aligns with the research tradition at Wingquist Laboratory.

DRM is well suited to this research for several reasons. It provides a structured path from problem understanding to solution development and empirical evaluation, which matches the progression across the three appended papers. It accommodates multiple research methods within a single coherent framework, which is necessary here since the work draws on literature review, numerical simulation, optimization, and case studies. It also explicitly addresses both scientific rigor and industrial applicability, reflecting the dual goal of producing methods that are academically sound and practically implementable.

3.2 Design Research Methodology

DRM structures design research into four stages, illustrated in Figure 3.1, each with defined objectives and deliverables [66].

Research Clarification (RC) establishes the foundation of the research. Through an initial review of the literature, the research goals are clarified, the research questions are formulated, preliminary success criteria are defined, and the scope of the work is determined. The outcome is an overall research plan that provides the focus for the subsequent stages.

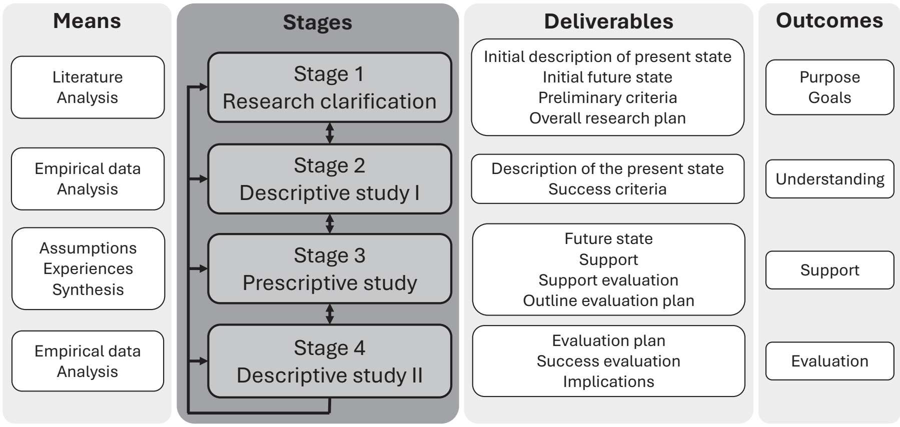

Figure 3.1: Design Research Methodology framework [66].

Descriptive Study I (DS-I) aims at understanding the existing situation in sufficient detail to inform the development of support. Through literature analysis or empirical study, the factors that influence the success criteria are identified, resulting in a consolidated description of the current state and a refined set of success criteria against which the research can later be assessed.

The Prescriptive Study (PS) develops the support intended to improve the situation described in DS-I, constituting the core contribution of the research. Development is accompanied by continuous Support Evaluation, in which the functionality and internal consistency of the support are assessed as it is built, and by the outline of a plan for its subsequent evaluation.

Descriptive Study II (DS-II) evaluates the developed support through empirical studies. Blessing and Chakrabarti [66] distinguish two types of evaluation in this stage: Application Evaluation, which assesses whether the support can be used as intended and affects the targeted factors as expected, and Success Evaluation, which assesses whether the support contributes to the success criteria. The process across the four stages is inherently iterative: insights from DS-II can feed back into refinement of the support or generate new understanding requiring a return to DS-I.

Each stage can be carried out to different depths: as a review-based study, drawing on the existing literature; as a comprehensive study, in which the researcher produces new results; or as an initial study, undertaken in less detail to round off a project and indicate directions for further evaluation. Based on the depth of each stage, Blessing and Chakrabarti [66] distinguish seven types of design research projects, a classification applied to this thesis in the following section.

3.3 Application of DRM in this thesis

Figure 3.2 illustrates how the DRM framework is applied throughout this thesis, mapping research questions to papers and DRM stages.

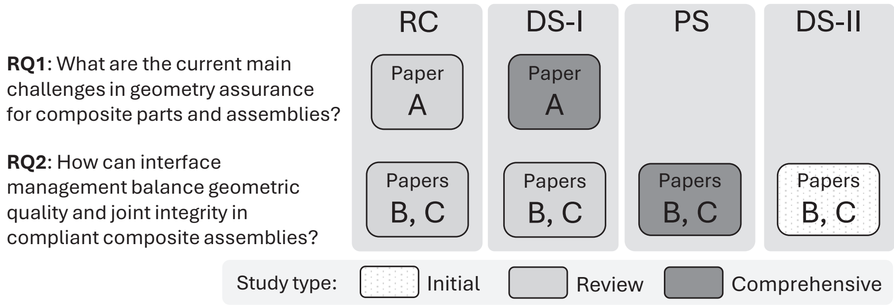

Figure 3.2: Application of DRM in this thesis, linking research questions, appended papers, and DRM stages.

RC was conducted through the formulation of the research questions and success criteria at the beginning of the project, informed by an initial literature study, later consolidated in Paper A. Papers B and C contribute to this stage through the problem motivation and scoping in their introductory sections. The success criterion for RQ1 is a structured mapping of the state of the art that identifies the open challenges in GA for composites and frames the subsequent work. The success criterion for RQ2 is a set of simulation-based methods that demonstrably manage interface variation while respecting structural constraints, with a quantifiable characterization of the effect on both geometric quality and joint integrity.

DS-I is primarily represented by Paper A, which reviews the state of GA for composite parts and assemblies, maps variation sources across manufacturing stages, and identifies the specific gaps in assembly simulation and design gap specification that motivate the prescriptive work. Paper A thereby addresses RQ1 and, in doing so, frames RQ2. Papers B and C also contribute to this stage through their respective reviews of the state of the art, which establish the problem understanding specific to shimming practice and design gap specification before the corresponding methods are developed.

The PS is represented by Papers B and C, which together address RQ2 from two complementary directions. Paper B operates at the assembly stage, developing a framework that derives the maximum allowable shim thickness from fastener joint mechanics and integrates this structural limit into a fixture adjustment optimization that reduces interface gaps. Paper C operates at the design stage, developing a parametric variation simulation approach that quantifies the influence of the design gap on shim thickness and post-assembly geometric deviation across populations of manufactured parts.

DS-II is also represented by Papers B and C, both of which use the same virtual case study: a CFRP wingbox section assembly representative of a typical aerospace primary structure. Paper B evaluates the framework by analyzing gap distributions, geometric deviations, and fastener stress criteria across ten simulated assemblies. Paper C evaluates the design gap sensitivity through a parametric sweep across multiple interface scenarios and two manufacturing populations of one hundred assemblies each.

In terms of the research types defined by Blessing and Chakrabarti [66], this thesis corresponds to a Type 5 project: a review-based RC, a comprehensive DS-I, a comprehensive PS, and an initial DS-II. The DS-I is considered comprehensive since Paper A goes beyond a summary of the literature: it organizes variation sources and GA challenges along the composite manufacturing and assembly process chain into a structured mapping of the field, published as a standalone, peer-reviewed contribution. The DS-II stage is thus only partially addressed: the developed methods are evaluated through virtual case studies, which demonstrate their applicability but do not constitute an evaluation in an industrial setting, and evaluation on physical components remains for future work. This reflects the position of the licentiate thesis as an intermediate stage in the overall research program.

3.4 Research methods

The research methods employed in this thesis are described following Säfsten and Gustavsson [67].

The literature study in Paper A was conducted as a structured review of GA for composite parts and assemblies. The review covered composite materials and manufacturing processes, geometric variation sources at each production stage, and existing GA and variation simulation tools. The selection of variation sources and references was focused on those most relevant to future GA challenges in the field. Sources were identified through database searches and snowballing, following references from key papers and identifying works that cited them [68]. A structured review was selected because RQ1 concerns the breadth of an existing body of knowledge rather than a specific technical mechanism, and a structured search complemented by snowballing reduces the risk of overlooking relevant subfields while allowing the identified challenges to be organized along the manufacturing and assembly process chain. The review was complemented by literature studies in Papers B and C, which introduce the specific tools and methods applied and compare them with previous research.

The primary research method in Papers B and C is modeling and simulation, which involves creating digital representations of real systems to understand behavior, predict outcomes, or optimize parameters [67]. Both papers apply the non-rigid variation simulation described in Section 2.4.2, which resolves the compliant behavior and contact forces that govern gap formation in thin composite assemblies [53], and which makes the large part populations of these studies computationally feasible. In Paper B, the simulation is coupled with a trust-region reflective optimization algorithm [63], in which the gap field is treated as a black box and locally approximated through finite differences, to compute optimal locator adjustments subject to structural constraints.

The case studies in Papers B and C are virtual, using numerically generated part populations representative of CFRP aerospace structures. Virtual case studies were preferred over physical experiments for three reasons. Physical trials on large-scale composite assemblies are prohibitively expensive at the exploratory stage of method development. Simulation permits independent control of the manufacturing signature, which is essential for isolating its effect on the optimal design gap and cannot be achieved with physically manufactured populations. Finally, simulated populations allow repeatable parametric sweeps over hundreds of assemblies, with statistical stability verified through convergence analysis of the accumulated mean.

3.5 Research quality

This section assesses the quality of the research process. The assessment draws on the verification concepts of Buur [69] and on the validity and reliability criteria described by Säfsten and Gustavsson [67]. The quality of the developed supports themselves, in terms of model verification and validation, is assessed separately in Section 5.4.

Logical verification is applied throughout the research by ensuring that results are consistent, coherent, and complete [69]. Results across Papers B and C are internally consistent, with no contradictory findings. Verification by acceptance is demonstrated through peer review: Papers A and B have been peer-reviewed and accepted for publication, and Paper C has been submitted and is under review.

Internal validity is supported by controlled virtual experiments in which specific variables are isolated, such as the effect of fixture adjustment magnitude on geometric deviation in Paper B, and the effect of individual interface design gaps in Paper C. External validity is partially limited by the use of simplified geometries and virtual part populations rather than full-scale industrial components, a common limitation in simulation-based GA research at this stage of method development; this limitation is acknowledged in the delimitations and assessed in detail in Section 5.4. Construct validity is ensured through the use of established metrics: RMS deviation for geometric quality, gap distributions for assembly quality, and Tsai-Hill criteria for structural loading assessment.

Reliability is supported by the deterministic nature of the simulation models, which produce identical results for identical inputs, by the controlled numerical precision of the simulation environment, and by the documentation of model specifications and population generation parameters, enabling the studies to be reproduced.

3.6 Ethical considerations

This research involves exclusively computational methods, with no human subjects, animal testing, or sensitive personal data. All simulation data, model specifications, and software implementations are documented to enable reproducibility, and data supporting published results are available upon reasonable request. No proprietary industrial data or trade secrets are disclosed. During this thesis preparation, a generative AI tool (Claude by Anthropic) was used to assist with language editing and clarity. All content was reviewed and approved by the author, who takes full responsibility for the published work. Generative AI tools were similarly used in preparing the appended papers, as declared therein in accordance with journal policies.

Chapter 4

Results

This chapter summarizes the appended papers and their contributions. The three papers are interconnected: Paper A establishes the research context and motivates Papers B and C, which address complementary aspects of the same underlying challenge, interface management in shimmed composite assemblies. Each paper is presented in turn through its background, method, main outcomes, and contribution.

4.1 Paper A: Challenges in geometry assurance for composites manufacturing

Background: Composite materials are increasingly adopted in aerospace structures, but their manufacturing processes introduce geometric variation sources that differ fundamentally from those of metallic parts. Despite this, GA tools and methods have been developed primarily for metallic assemblies. A structured assessment of their applicability to composites, and a mapping of the open challenges, was lacking in the literature.

Method: A structured literature review was conducted, identifying and categorizing variation sources at each stage of composite manufacturing, including cutting, placing, curing, machining, and assembly. The applicability of existing GA tools, including commercial CAT software such as RD&T and 3DCS, was critically assessed against the specific requirements of composite simulation.

Outcome: The review showed that while process simulation for composites has advanced considerably, several gaps remain in GA. At the part level, the dominant variation modes are spring-in and warpage, which produce a manufacturing signature that is difficult to incorporate into standard variation simulation workflows. Metallic forming processes such as stamping also produce systematic signatures, but these are comparatively small, and because the processes are mature, they are well characterized and enter assembly analysis as established statistical distributions. The composite signature is larger and more strongly design-specific, and it is not yet routinely available in this form, so it must be represented explicitly rather than drawn from a known distribution. At the assembly level, the compliant behavior of thin-walled parts, the management of interface gaps, and the absence of simulation-based guidance for shimming strategies and design parameters such as interface clearances were identified as key open challenges. These findings directly motivated the research questions addressed in Papers B and C.

Contribution: Paper A provides a structured overview of the state of the art in GA for composites, identifying the specific gaps that define the research agenda for the remainder of this thesis.

4.2 Paper B: Gap reduction vs. geometric deviation: a trade-off in composite assembly

Background: Building on the gaps identified in Paper A, Paper B addresses the management of interface gaps in compliant CFRP assemblies. Fixture locator adjustment is an established technique for reducing gaps by optimizing the fixture configuration based on measured part geometry. However, shimming introduces bending stresses in fasteners that scale with shim thickness, imposing structural limits on acceptable gap fill. No framework existed that jointly considered these structural constraints and the geometric consequences of fixture optimization for composite assemblies.

Method: A simulation-based framework was developed that derives maximum allowable shim thickness analytically from fastener joint mechanics, based on part thickness, fastener diameter, and an allowable increase in fastener von Mises stress. These limits were incorporated as constraints in a fixture optimization minimizing interface gaps, formulated as a constrained black-box problem and solved with a trust-region reflective algorithm using finite-difference approximations of the gap field. The complete assembly process was simulated in RD&T using non-rigid variation simulation, covering fixturing, contact, gap prediction, shimming, fastening, and springback. The framework was applied to a simplified CFRP wingbox section comprising five parts and 89 fasteners, with ten assemblies generated from numerically simulated part populations. The assembly, its positioning system, and the fastener layout are shown in Figure 4.1.

Outcome: Fixture adjustment reduced average RMS interface gaps by 43%, from 0.185 mm to 0.103 mm across the ten assemblies. However, post-assembly geometric deviations increased in seven out of ten cases, as shown in Figure 4.2, with average RMS nodal displacements growing from 0.641 mm to 1.004 mm. A positive correlation was found between adjustment magnitude and Tsai-Hill stress criteria ($r = 0.75$), and between the Tsai-Hill criteria and the resulting geometric deviations ($r = 0.73$); with ten assemblies these correlations are indicative of the mechanism rather than statistically conclusive, as discussed in Section 5.4. These results reveal that gap minimization and geometric accuracy are conflicting objectives in compliant composite assemblies. The mechanism is visible in the correlation chain: larger fixture adjustments force the deviated parts into contact to close the gaps, raising the locked-in stresses, and these

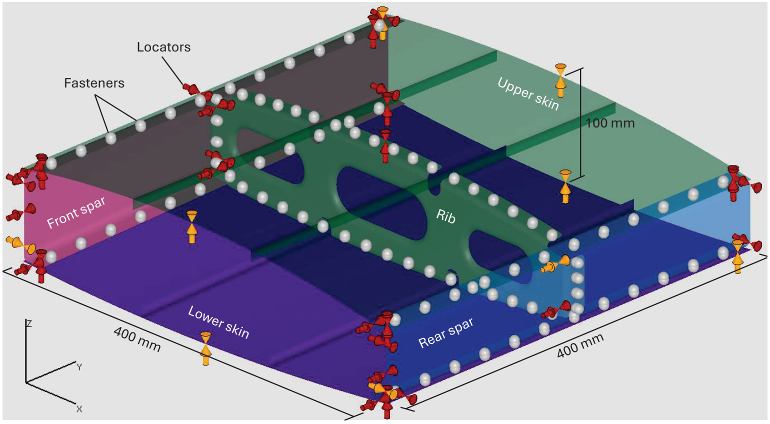

Figure 4.1: The wingbox section case study, with positioning system, fasteners, and main dimensions.

stresses, on release of the fixture, relax into larger global deviations, so the very adjustments that reduce local gaps displace the assembly from its nominal geometry.

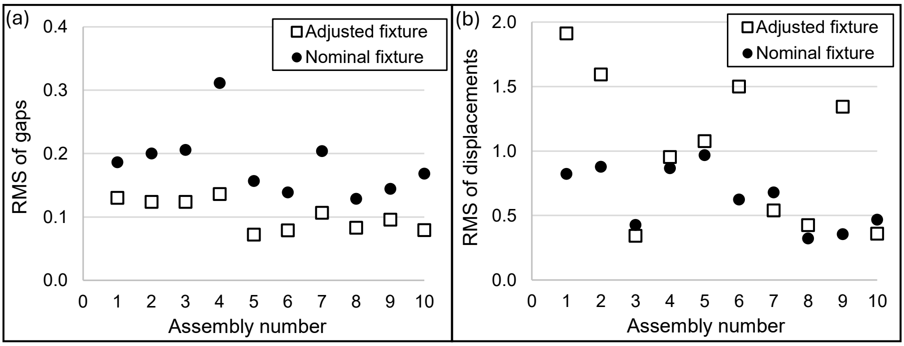

Figure 4.2: (a) Interface gap RMS and (b) post-assembly deviation RMS for the ten assemblies, before and after constrained fixture adjustment. Data from Paper B.

Contribution: Paper B provides a framework for structurally constrained fixture optimization in shimmed composite assemblies, and identifies a fundamental trade-off between local gap reduction and global geometric accuracy that must be considered when planning assembly strategies. The framework is suited to digital twin environments where inspection data from individual parts informs fixture setup before assembly.

4.3 Paper C: Design gap specification in shimmed composite assemblies

Background: Paper B revealed a trade-off between gap reduction and geometric accuracy at the assembly stage. A complementary question arises earlier, at the design stage: how the design gap, the intentional interface clearance prescribed in the nominal CAD geometry, should be specified. When present, the design gap influences both shimming requirements and post-assembly geometric deviation across a population of parts. This specification currently relies on engineering judgment, and no quantitative simulation-based guidance existed.

Method: A parametric variation simulation framework was developed using non-rigid variation simulation across two populations of 100 virtual assemblies each, based on the same wingbox geometry as Paper B (Figure 4.1). Population 1 was generated with a consistent directional spring-in signature; Population 2 was centered at zero deviation. Design gaps were prescribed numerically via the contact detection distance, avoiding the need to regenerate part geometry for each configuration. A parametric sweep from 0 to 0.5 mm was conducted across individual interfaces and the all-interfaces scenario for both populations.

Outcome: The results revealed a non-monotonic relationship between design gap and post-assembly geometric deviation, shown in Figure 4.3. A design gap of approximately 0.3 mm minimized geometric deviation for Population 1 and marked the point of saturation for Population 2. Below this value, fixturing forces introduce deformations that increase deviation, while beyond it the shim thickness continues to grow without geometric benefit.

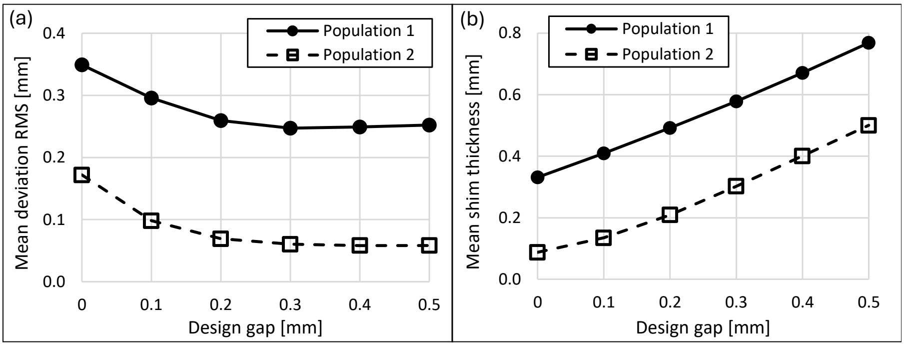

Figure 4.3: (a) Mean post-assembly geometric deviation RMS and (b) mean shim thickness RMS as functions of the design gap for the All/All interface scenario, for both manufacturing populations. Data from Paper C.

This behavior is explained by the interface contact forces: below the optimum the prescribed clearance is too small to absorb the manufacturing deviation, so parts are forced into contact during fixturing and deform, while above it the contact forces have already fallen to near zero, so further clearance adds shim thickness without reducing deformation. The magnitude of the improvement was sensitive to the manufacturing signature, with a 29% deviation reduction for Population 1 and 66% for Population 2, yet the optimal gap value remained consistent between the two populations despite this difference. Interface sensitivity analysis further identified the Rear Spar and Rib as the most influential interfaces on assembly-level geometric deviation.

Contribution: Paper C provides a parametric simulation framework for design gap specification in shimmed CFRP assemblies, demonstrating that an optimal design gap exists and that its value is robust to differences in manufacturing signature. The findings provide quantitative, simulation-based guidance for a design parameter previously set by engineering judgment.

Chapter 5

Discussion

This chapter discusses the results of Chapter 4 in relation to the research questions and draws the contributions of the three appended papers into a coherent view of geometry assurance for shimmed CFRP assemblies. It answers the research questions, states the scientific and industrial contributions, evaluates the verification and validation of the developed supports, and outlines future work.

5.1 Answers to the research questions

RQ1: What are the current main challenges in GA for composite parts and assemblies?

Paper A established that the geometry assurance tools developed for metallic assemblies do not transfer directly to composites. Metallic parts also deform systematically, for example through springback after forming, but this deformation is typically compensated at the part-manufacturing stage, so that the residual variation entering assembly analysis is smaller and can be treated as an empirical statistical distribution rather than a simulated mean shape. Composite parts differ in two ways: they introduce variation sources that have no equivalent in metal parts, and their PID is large and coupled enough that it must be represented in the variation simulation itself rather than handled separately.

These challenges fall into two connected groups. At the part level, curing causes spring-in and warpage, systematic and design-specific shape distortions that form a manufacturing signature, larger and harder to predict than metallic springback because they arise from the coupled effects of layup, cure cycle, and tool-part interaction. Standard variation simulation does not routinely incorporate such a large deterministic mean shape, so the part-level input to an assembly analysis is poorly represented. At the assembly level, the parts are thin and compliant, so they deform when they are fixtured and joined, and the interface gaps that result must be filled with shims rather than closed by force. Simulation-based guidance for managing these gaps, through shimming strategies and design parameters such as interface clearances, was largely missing.

The two groups are linked. The systematic signature created during curing is what carries over into the assembly as an interface gap with a systematic, non-random component, so the part-level and assembly-level challenges are two sides of the same problem: a fixed, design-specific deviation that current tools neither represent well at the part level nor manage at the assembly level. Among these challenges, interface management was selected as the focus of RQ2, because it is where this propagated variation must satisfy two competing requirements at once: geometric quality and joint integrity. This structured mapping, and the selection it motivates, fulfill the success criterion defined for RQ1.

RQ2: How can interface management balance geometric quality and joint integrity in compliant composite assemblies?

Papers B and C answer this question jointly, addressing the interface from the two stages of the product realization process where it can be influenced: the assembly stage and the design stage.

At the assembly stage, the results of Paper B show that joint integrity can be protected by deriving shim thickness limits from fastener joint mechanics and imposing them as constraints on fixture adjustment, but that geometric quality does not follow automatically: gap reduction and geometric accuracy proved to be conflicting objectives. The balance RQ2 asks about must therefore be struck deliberately, and the framework of Paper B provides the quantitative basis for doing so.

At the design stage, the results of Paper C show that the design gap is an effective lever for this balance, since an optimal value exists that minimizes geometric deviation while avoiding the unnecessary shim thickness, and associated fastener loading, that larger gaps incur. The robustness of the optimal value across manufacturing signatures indicates that the design gap can be specified before the manufacturing process is fully characterized, which is what makes it usable as an early design guideline.

Together, the two papers establish that interface management balances geometric quality and joint integrity through complementary levers, structurally constrained adjustment during assembly and informed gap specification during design, and that in both cases the balance can be quantified rather than left to engineering judgment. This fulfills the success criterion defined for RQ2: the two methods manage interface variation while respecting the structural shim limit, and they quantify its effect on geometric quality, through the gap-deviation trade-off and the design-gap response, and on joint integrity, through the shim-induced stress bound, although the latter is evaluated using a conservative structural margin, demonstrating a framework that can absorb certification-specified structural requirements without modifying the underlying optimization derivation.

5.2 Scientific contribution

The scientific contributions of this thesis are:

- A structured mapping of the state of the art in GA for composites, identifying the variation sources and simulation challenges that distinguish composite assemblies from metallic ones, and the open research directions that follow from them (Paper A).
- A simulation-based framework for fixture adjustment optimization in compliant CFRP assemblies, incorporating fastener-derived shim thickness limits as structural constraints. Its application identified and quantitatively characterized a trade-off between local gap reduction and global geometric accuracy (Paper B).
- A parametric variation simulation framework for design gap specification in shimmed CFRP assemblies, including a contact-detection-distance method that prescribes design gaps numerically without regenerating part geometry. Its application demonstrated that an optimal design gap exists, minimizing post-assembly geometric deviation and remaining robust to differences in manufacturing signature (Paper C).

5.3 Industrial contribution

The industrial relevance of this thesis follows from its motivation in an industrial problem: the shimming of composite assemblies is a costly, measurement-intensive step on the critical path of assembly. The methods developed here are aimed at reducing this cost in two ways. By predicting the interface gaps that remain after fixturing, the framework of Paper B allows shims to be prepared in advance rather than measured and fitted during assembly, moving a time-consuming step off the critical path. By identifying the design gap that minimizes post-assembly deviation, Paper C reduces both the shim thickness required and the rework that an unsuitable clearance would otherwise incur.

- The review in Paper A provides industry practitioners with a structured assessment of the limitations of current GA tools for composites and a roadmap of the simulation capabilities needed to support composite assembly in production environments. It is of direct use in tool selection and in identifying where existing metallic-oriented workflows must be extended before they can be relied upon for composite structures.
- The framework developed in Paper B is suited to digital twin environments where individual part inspection data can be used to compute optimal fixture settings and pre-manufacture shims before assembly begins, with the potential to reduce the measurement and disassembly steps that conventional fit-up requires. Realizing this benefit in practice depends on conditions that the virtual studies assume: inspection data of sufficient density and accuracy to drive the simulation, an adjustable fixture capable

of executing the computed settings, and integration with the CAT software already used in the production chain.

- The design gap guidance from Paper C provides a quantitative, simulation-based basis for an early-stage design parameter previously set by engineering judgment, one that directly influences both shimming requirements and assembly geometric quality. Because the optimal value proved robust across manufacturing signatures, it can be specified early, before the process is fully characterized, which is when design decisions are actually made. Applying the method to a new structure, however, does not mean reusing the 0.3 mm value found here: it requires building a variation simulation model of that structure and an estimate of its expected manufacturing deviation, from which the appropriate design gap for that specific case is obtained.

The distance between these results and routine industrial use is the same in each case: the methods are demonstrated on a virtual case study, and their adoption requires the supporting infrastructure, inspection, adjustable fixturing, and validated process-deviation models, to be in place. The contribution is therefore methodological: the methods are demonstrated in simulation and provide quantitative guidance that industry can use, while their integration into production practice depends on supporting infrastructure and on case-specific modeling that lie outside the scope of this work.

5.4 Verification and validation of the developed supports

While Section 3.5 addressed the quality of the research process, this section evaluates the supports developed in the thesis: the constrained fixture adjustment framework of Paper B and the design gap specification framework of Paper C. For simulation-based supports, verification addresses whether the models are implemented and solved correctly, while validation addresses whether they adequately represent the real assembly process for their intended use [70]. In DRM terms, the verification activities correspond to the Support Evaluation conducted during the PS stage, while the case-study-based validation corresponds to the Application Evaluation of an initial DS-II [66]; a Success Evaluation, assessing the supports' contribution to the success criteria in an industrial setting, lies beyond the scope of this thesis.

Verification: The framework of Paper B was verified through consistency checks of the simulation outputs, convergence of the optimization algorithm to its termination criteria for each assembly, and confirmation that the structural constraint was respected in all optimized cases. The framework of Paper C was verified through convergence analysis of the Monte Carlo mean, confirming that 100 samples per population are sufficient for statistically stable results, and through comparison of the numerical design gap prescription against the explicit geometry modification approach [70], which showed agreement within acceptable limits and confirmed that the numerical approach is mechanically equivalent for the purposes of this study.

Validation: Both supports were evaluated through virtual case studies on a simplified CFRP wingbox section representative of an aerospace primary structure.

For Paper B, the evaluation demonstrated consistent gap reduction across ten assemblies with part instances drawn from numerically generated populations, while revealing the trade-off with geometric accuracy. The ten-assembly sample is sufficient to demonstrate the trade-off and its mechanism, but the reported correlations between adjustment magnitude, fastener stress, and geometric deviation are indicative rather than statistically conclusive; confirming their strength would require a larger population, in contrast to the design-gap study of Paper C, where convergence of the Monte Carlo mean over one hundred assemblies per population was verified.

Joint integrity is addressed in Paper B through a conservative structural margin rather than a full certification analysis: the shim thickness limit is derived by capping the additional von Mises stress introduced by the shim at 15% relative to the unshimmed joint, a deliberately conservative value chosen to reserve capacity for in-service loads. This value is an engineering choice rather than a certification requirement, and the framework itself is independent of it, since a different allowable increase, set by a specific structural requirement, yields a correspondingly different limit through the same derivation.

For Paper C, the evaluation demonstrated the existence and robustness of an optimal design gap across two manufacturing populations with different signatures. The validation is, however, limited in three respects. The case studies rely on virtual assemblies with numerically generated part populations rather than physical inspection data; the underlying non-rigid variation simulation methods are well established for compliant assembly analysis [53], [71], but validation on physical CFRP assemblies would strengthen confidence in the predictions. A single, simplified wingbox geometry was used, and the identified trade-off and optimal gap value may manifest differently in assemblies with other part counts, stiffness distributions, or fastener configurations. Finally, broader design guidelines would require evaluation across different assembly geometries and material systems. The findings are therefore best interpreted as simulation-based predictions that provide quantitative guidance for design and assembly decisions, subject to the geometric and material assumptions of the simulation models.

5.5 Future work

The results of this thesis suggest several directions for future research. The trade-off identified in Paper B between gap reduction and geometric accuracy calls for a multi-objective optimization framework that simultaneously minimizes interface gaps and post-assembly geometric deviations, rather than treating them as separate objectives. Alternative shimming strategies, including selective shimming and the use of discrete peelable shims, should also be explored within this framework.

The design gap study in Paper C was conducted on a single wingbox geometry with two manufacturing populations. Future work should investigate the sensitivity of the optimal gap value to part geometry, assembly configuration, and material system, to establish broader design guidelines applicable across different composite aerospace structures.

An extension of both papers is the integration of PID predictions into the assembly simulation workflow. Currently, part deviations are modeled as numerically generated populations representative of spring-in behavior, but without explicit process simulation input. Incorporating draping simulation, which determines the local fiber orientations that govern PID, into curing simulation would enable both the prediction and the minimization of part-level deformation, and using these predictions as the source of part deviations in assembly simulation would close the loop between composite manufacturing and assembly GA. In the longer term, these elements point toward an integrated, simulation-based GA framework spanning the complete process chain, from part manufacturing to final assembly, in which manufacturing, design, and assembly decisions are evaluated against their combined effect on final geometric quality.

Finally, experimental validation on physical CFRP assemblies would strengthen the conclusions of both papers. The underlying non-rigid variation simulation methods have been validated against physical measurements in previous studies [53], [71], so the remaining validation need concerns the framework-level predictions, the trade-off between gap reduction and geometric deviation and the optimal design gap value, rather than the simulation methods themselves. While the virtual case studies demonstrate the methods on geometries representative of aerospace primary structures, demonstration on full-scale industrial components would be a valuable complement, though it lies outside the simulation-based scope of this research program.

Chapter 6

Conclusions

This thesis has addressed GA in shimmed compliant CFRP assemblies through three appended papers, developing simulation-based methods to support interface management from design to assembly. The following conclusions are drawn in response to the research questions.

RQ1: What are the current main challenges in GA for composite parts and assemblies?

GA tools developed for metallic assemblies require significant adaptation for composites. Metallic manufacturing is mature and its part variation is well characterized, so it enters assembly analysis as established statistical distributions. For composites, the anisotropy of the laminate and the coupled, multi-stage manufacturing process give rise to a PID that is large, systematic, and design-specific. This deviation is less readily captured as a statistical distribution and must instead be represented explicitly in the variation simulation. At the part level, curing produces spring-in and warpage, the systematic distortions that constitute this signature. At the assembly level, the compliant behavior of thin-walled parts, the management of interface gaps, and the absence of simulation-based guidance for shimming strategies and design parameters such as interface clearances represent the key open challenges. These two levels are connected: the systematic signature created during curing is what propagates into the assembly as the interface gap that must then be managed, making interface management the central challenge addressed in the remainder of this thesis.

RQ2: How can interface management balance geometric quality and joint integrity in compliant composite assemblies?

Interface management can balance geometric quality and joint integrity through two complementary levers, one at the assembly stage and one at the design stage. At the assembly stage, fixture adjustment optimization constrained by fastener-derived shim thickness limits can significantly reduce interface gaps while keeping shims within structurally acceptable bounds. However, gap reduction is accompanied by increased post-assembly geometric deviation in the majority of cases, revealing that local gap minimization and global geometric accuracy are conflicting objectives that cannot be simultaneously optimized through single-objective fixture adjustment, and that both must be jointly considered when planning assembly and shimming strategies.

At the design stage, the design gap has a significant and non-monotonic influence on post-assembly geometric deviation. An optimal design gap of approximately 0.3 mm minimizes geometric deviation across populations with different manufacturing signatures, while larger gaps increase shim thickness, and with it fastener loading, without geometric benefit. The consistency of the optimal value across manufacturing populations indicates that it is robust to variation in the manufacturing process and can serve as a quantitative basis for simulation-informed design gap specification. In both cases, the balance between geometric quality and joint integrity is quantified rather than left to engineering judgment, and simulation-based methods prove necessary to characterize and exploit these levers effectively.

The work contributes to the broader goal of GA for composite structures and lays the foundation for future research integrating PID predictions into assembly simulation, extending toward a simulation-based GA framework spanning the complete process chain, and validating the framework-level predictions on physical CFRP components.

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