User Requirements for an As-Manufactured Composite Part Data Standard (CompoSt)

Record of revisions

Issue	Date	Page	Para	Reasons for revision
1.0	20/06/2024			First release

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Summary

Today there is no standardised way to capture the properties of a composite part that has been manufactured, nor to compare this “as-manufactured” part to the original design intent, so that we can run a digital concessions process or analysis to improve our manufacturing process.

The best available format was developed by Dassault on the ZAero Horizon 2020 project, and is known as “HDF5 for composite manufacture”, and built on a previous format “HDF5 for composite CAE” that has been adopted by approximately 16 companies. Other formats of interest are STEP AP214 and QIF, although none of these are able to meet the requirements laid out in this document.

We have recorded the requirements for that format in this document. In scope for the data included are a Model Based definition (the “nominal definition” in these user requirements), and the as-manufactured state.

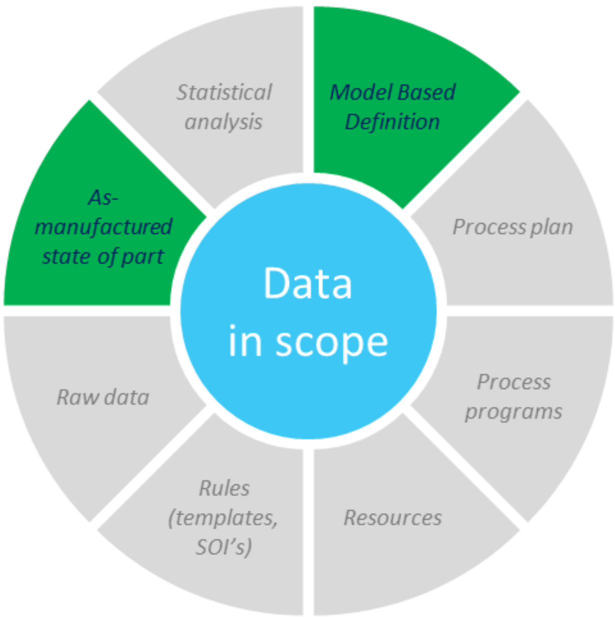


Figure 1: Data in (highlighted in green), and out of scope for the data format

A map of the data to be described within the data format is given in in Figure 2 below. This document explains the description given here and lays out the requirements on a data format that must be able to represent this ontology, and be intercompatible with other software and platforms.

Figure 2: description of a composite part

Contents

1 Document scope and objective

This document is a user specification for a “composite part as-manufactured data format”. It records the requirements on the data format, not the response to those requirements.

2 Introduction to as-manufactured composite parts

2.1 What is a composite part?

The broad definition for a composite is: anything made from more than one constituent material. For the purposes of this document and data format we are referring to the families of polymer matrix composites (PMCs), ceramic matrix composites (CMCs), and metal matrix composites (MMCs). These are composite products that include a fibre constituent of Carbon, Glass, Basalt, a Ceramic, a metal, etc., and a resin constituent of a thermoset plastic, thermoplastic, ceramic, metallic, etc.

2.2 What is an as-manufactured composite part?

To be of value during the design and manufacturing processes, and to describe the as-manufactured state of a composite part, we need the data format to describe:

1. The nominal definition of the part (as-designed)
2. The as-manufactured state of the part (as-manufactured)
3. The QA decisions that were made about the part
4. Traceability (including an event log, but this is mostly built into the other data)

Figure 3: basic building blocks of as-manufactured composite part data

3 Nominal definition

The following image describes the ontology (properties & their relationships) of the definition of a composite part.

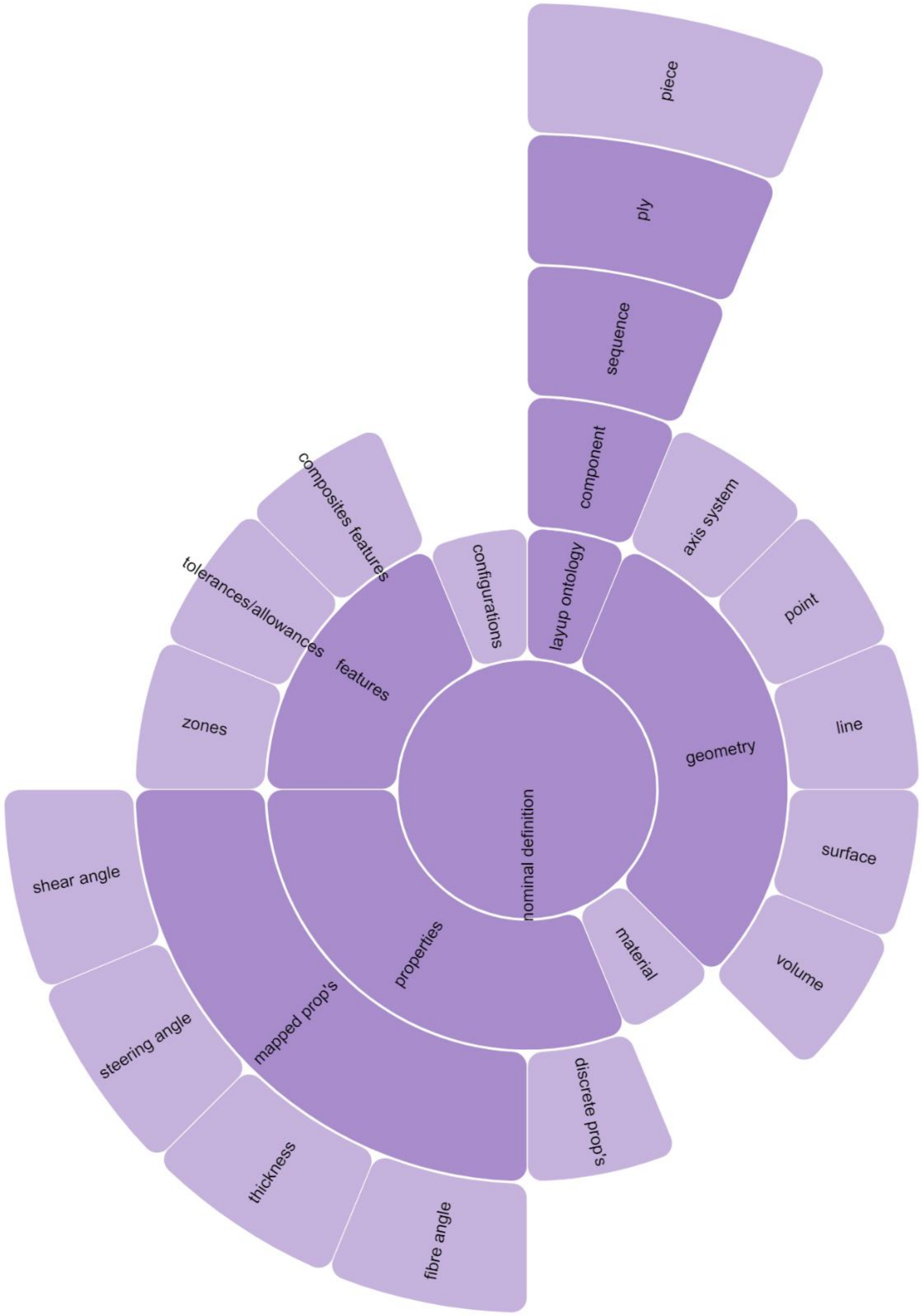


Figure 4: Definition of a composite part

3.1 Layup ontology

3.1.1 Generic layup ontology of a composite part

The following method of describing a composite part as a tree structure derives from existing CAD modelling tools (CATIA CPD, HDF5 for composites CAE). We will refer to this structure as the part ontology (the architecture would include the geometric design).

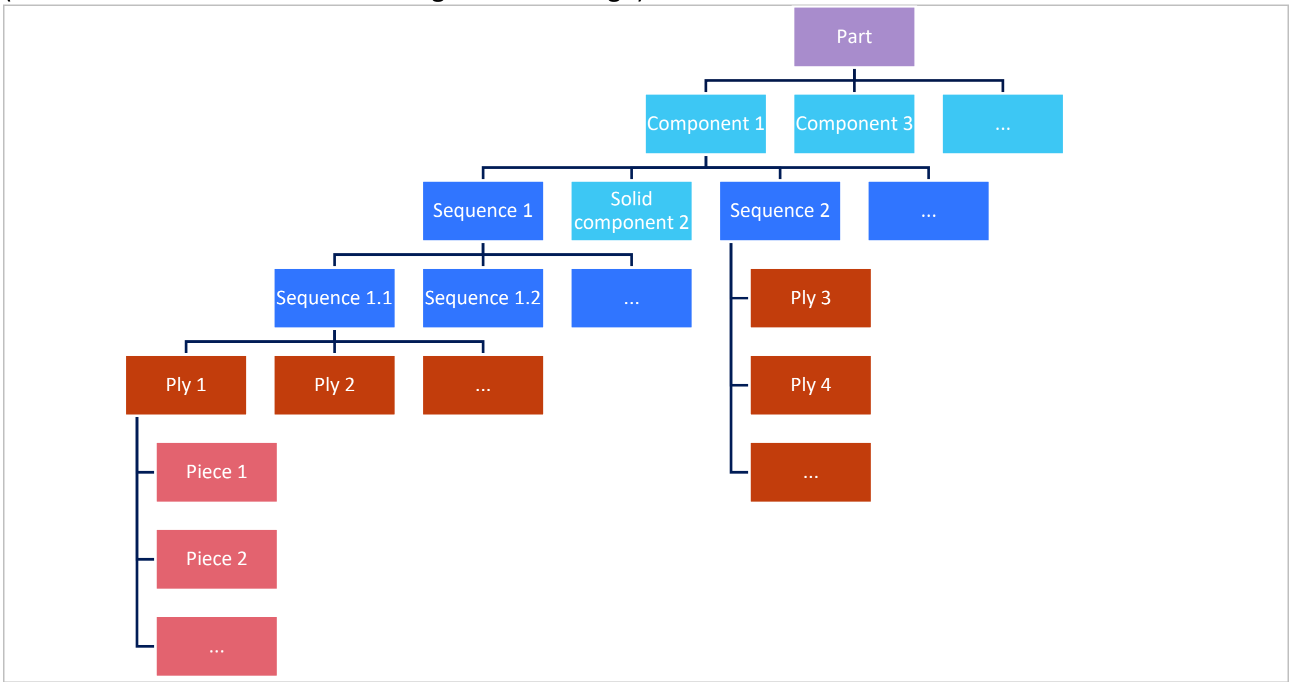


Figure 5: Generic architecture of a composite part

3.1.2 Composite part

A composite part could simply consist of a single laminate structure or be an assembly of sub-components co-cured or co-bonded to each other. Sub-components could include: composite components (laminates), core materials, inserts, and repairs.

3.1.3 Composite component

A composite component is defined as a contiguous laminate structure which may form a constituent of or the whole of a composite part. A composite component can contain one or more sequences of plies and may contain additional sub-components. Those sub-components can be composite components themselves (they may have been manufactured separately, to be dropped in place into the larger part), core material, or inserts. Sub-components should be enveloped by the parent component (otherwise they would be considered to be components in their own right and sit at the same level in the tree as the composite component).

3.1.4 Solid component

A solid component is any component composite or otherwise that either does not have a laminate structure, or where we do not wish to describe the laminate structure.

3.1.5 Sequence

Sequences are a theoretical construct to allow us to group plies into a group of plies usually sequentially uninterrupted by any other component.

3.1.6 Ply

Plies are made up of one or many pieces of a single material, in a single layer, and usually with a similar orientation. The material that makes up a ply may be multi-layered and/or multi-directional (in another sense: some materials can be made up of a combination of sub-materials).

3.1.7 Piece

Pieces are the individual pieces of material that make up a ply. There may be one or many in a ply. For an example of a multi-piece component see 3.1.11 Example of an AFP part below.

3.1.8 Example of a fabric layup part

In the case of fabric layup (manual or automated): components consist of discrete layers of fabric material which can be represented in the ontology without issue.

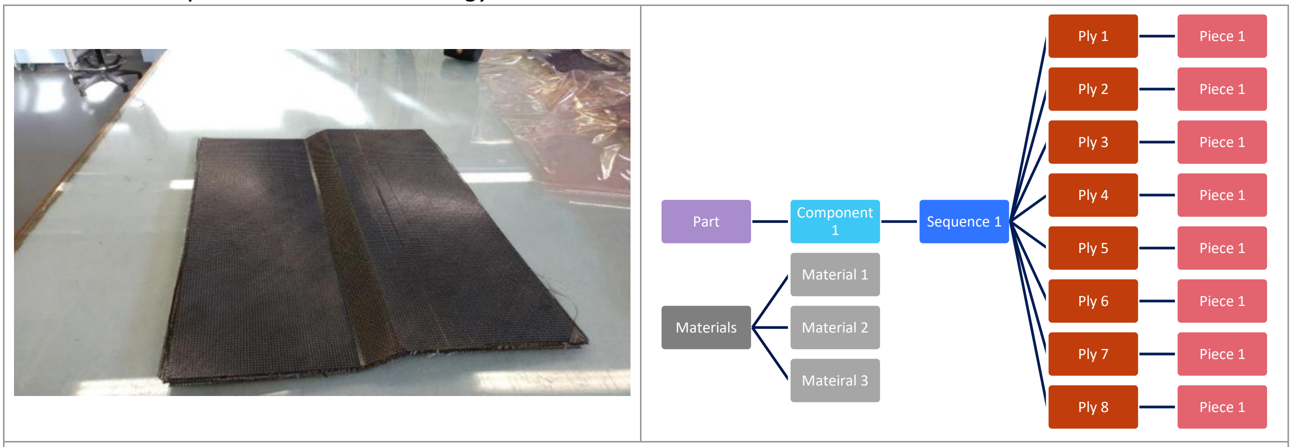
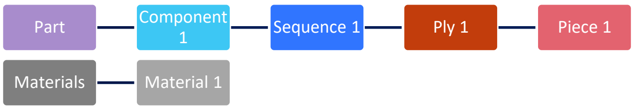


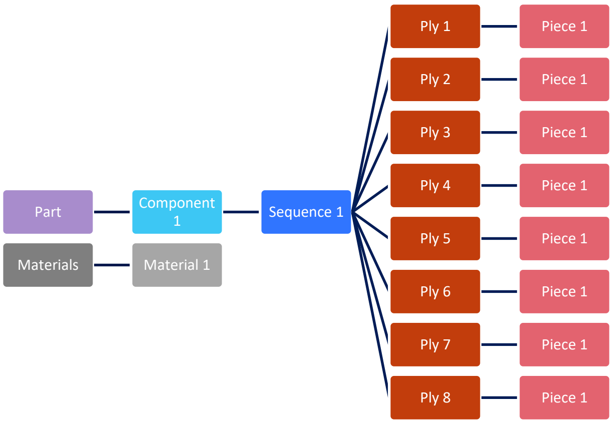
Figure 6: A fabric layup part & its layup ontology

3.1.9 Example of a continuously wound part

In the case of continuously wound components: it is possible to represent a continuously wound component that consists of a single tow of material as a single ply that wraps around upon itself many times. Perhaps in this context the concept of a ply starts to break down though. Alternately, we can describe the architecture as being multi-layered by artificially splitting the tow definition up in the CAD file where it does not in fact split in real life – this enables us to define plies that are single layer and don't overlap themselves. We may need to record where one piece is joined to the next with a continuous fibre though.



Layup ontology 1: single continuous piece, wrapped upon itself

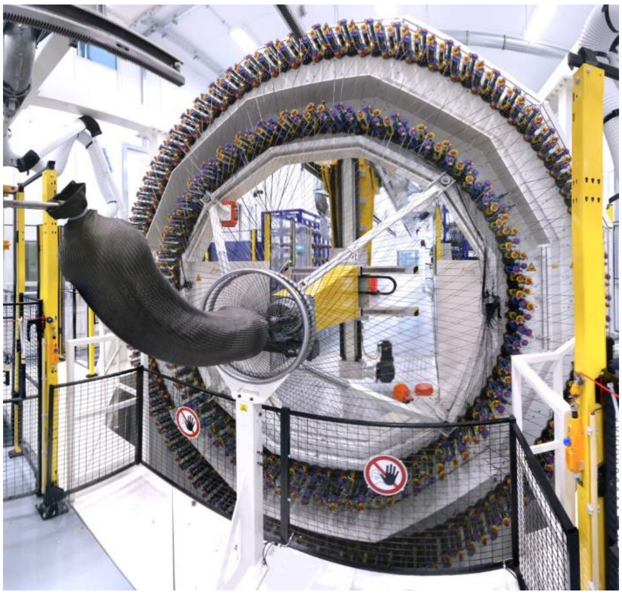


Layup ontology 2: Many separate pieces, each representing a single layer

Figure 7: A continuously wound composite part & two potential layup ontologies

3.1.10 Example of a braided part

In the case of manufacturing parts on a braider: the material and the component are being created at the same time and we must define the material as having fibres in each of the braiding axes, a single ply being a single pass of the braider.



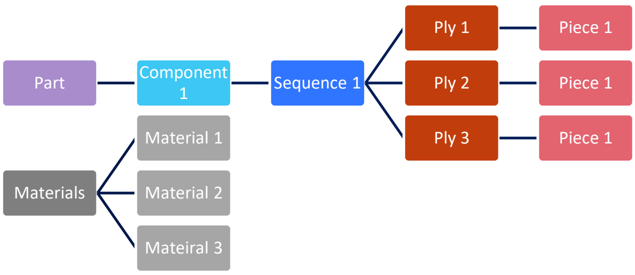


Figure 8: A braided part & its layup ontology

3.1.11 Example of an AFP part

In the case of Automated Fibre Placement: a single ply might be manufactured of hundreds of individual tows, each of which can be described as a single piece. Describing these tows as individual pieces allows us to measure the gaps and overlaps between them, and to mark individual tows that have been replaced to remove defects in them as such.

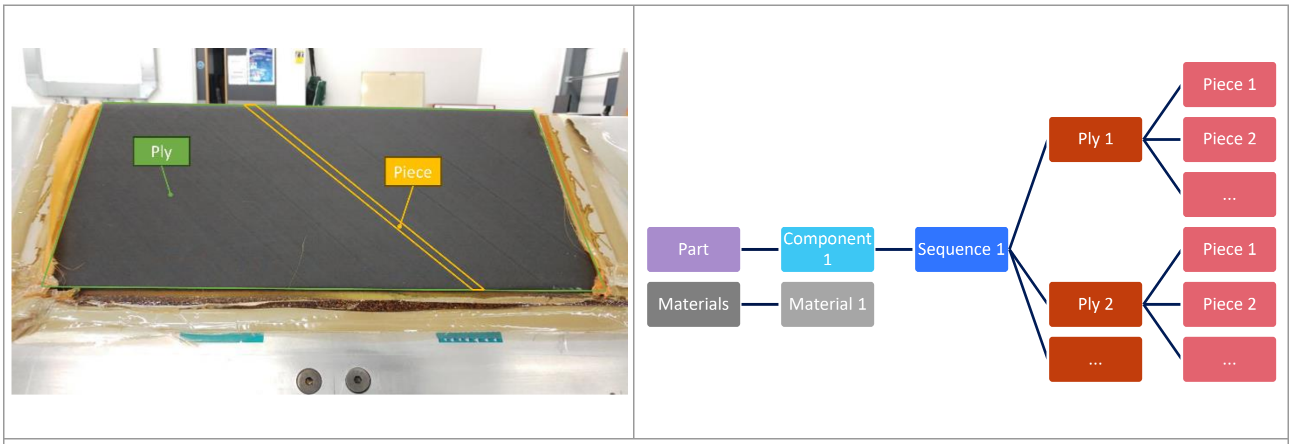


Figure 9: An AFP part & its layup ontology

3.2 Geometry

3.2.1 Geometry required to define a composite part

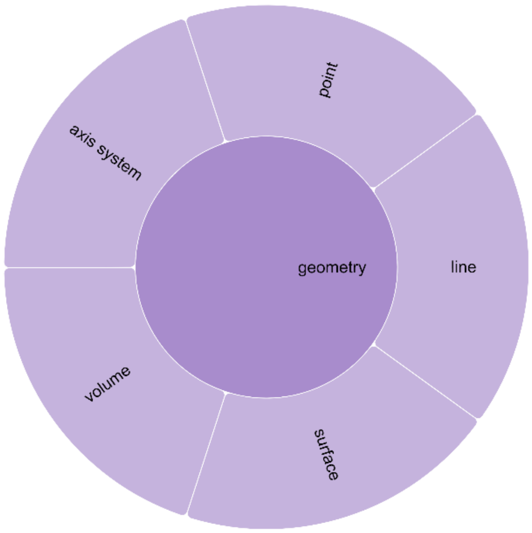


Figure 10: Geometry types required to describe a composite part

Typically, the minimum amount of geometry we need to describe a composite component is:

- **a surface** that describes the shape of one of the mould lines (a base surface),
- ply boundaries as **lines** or chains of lines, and
- a rosette or **axis system** to define layup direction.

More complicated parts that consist of multiple components would simply require more of the same types of geometry.

With this definition we are missing the nominal z-positions and thicknesses of each ply, although that can be mapped as data onto the base surface rather than being stored as geometry. Alternatively, we could store a **surface** describing the top and/or the bottom of each ply, or even for each cut piece. What we do choose to use to define our part might be dependent on the level of fidelity we want to achieve.

We may also wish to describe the part, or components within the part, as solid **volumes**. This enables us to describe and inspect the as-cured composite, and to describe any solids that are included within the composite part *e.g. core material and inserts.*

Points are required in order to define data during manufacturing *e.g. a thickness measurement taken at a specific point.*

All of these geometry types must be suitable to describe any shape in three dimensions that can be imagined. *e.g. straight lines alone cannot be used to describe a curved boundary line.*

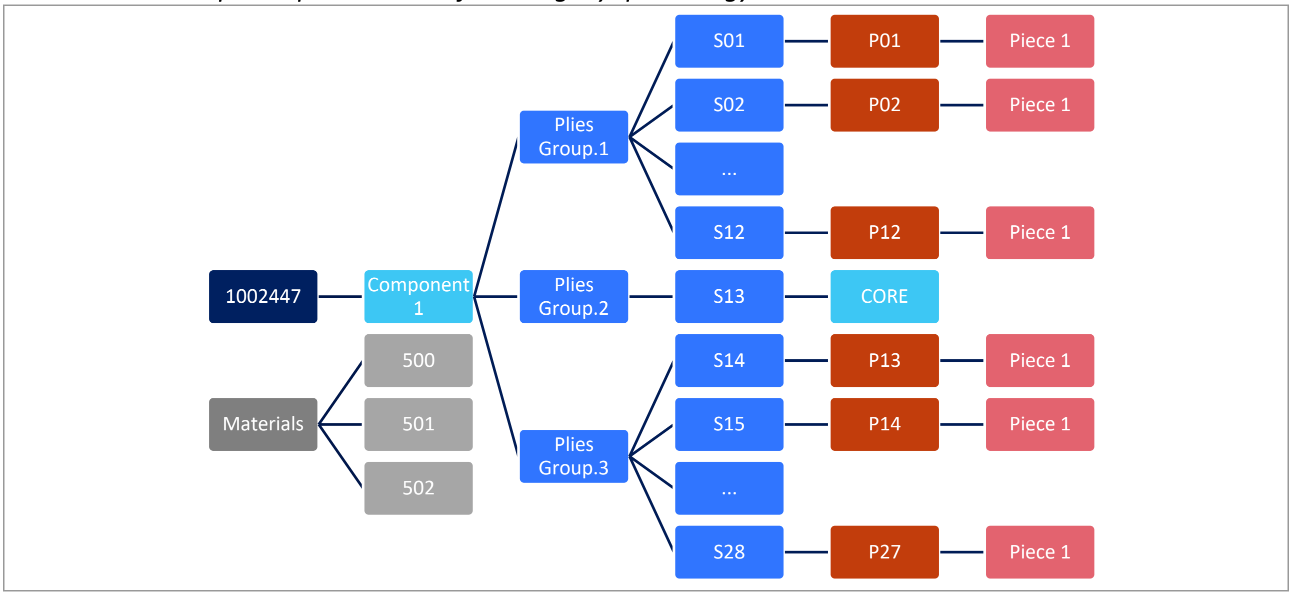
Tolerances, datums, features, and zones can all be mapped to the geometric definition geometry, but there may be cases where the definition geometry is not suitable to map a particular feature, so we must be free to define additional geometry to map these against.

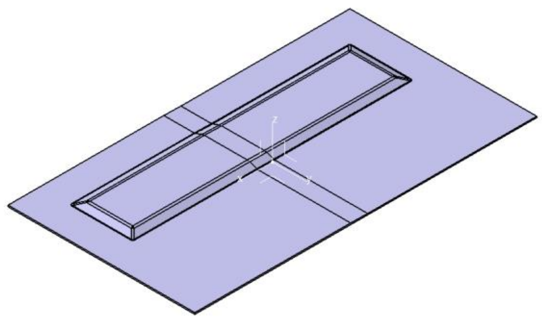
There are some processes that require some additional information, e.g. AFP requires tow boundaries, a Tow Add position, Tow Cut position, and a tape centreline.

Part data can be mapped to the part geometry directly, however, we might need to define additional modified copies of the definitions of some of the geometry, where the position of the actual ply or component deviates from the CAD nominal, the results of any inspection data must often be mapped to the correct location relative to the ply (rather than the part or tool reference system, which is how they are collected). This requires storing an "actual" definition of the geometric condition of the part, component, ply, or piece.

3.2.2 Example part for illustration of geometric concepts

We created a composite part with the following layup ontology:





-200 LAYUP TABLE								
PLY GROUP	SEQUENCE	PLY	ITEM No	ROSETTE	ZONE			
					S25	S24	S19	S20
Plies Group.1	S01	P01	501	ROSETTE	INDIFFERENT	INDIFFERENT	INDIFFERENT	INDIFFERENT
	S02	P02	500	ROSETTE	45	45	45	45
	S03	P03	500	ROSETTE	135	135	135	135
	S04	P04	500	ROSETTE	0	0	0	0
	S05	P05	500	ROSETTE	45	45	45	45
	S06	P06	500	ROSETTE	90	90	90	90
	S07	P07	500	ROSETTE	90	90	90	90
	S08	P08	500	ROSETTE	135	135	135	135
	S09	P09	500	ROSETTE	0	0	0	0
	S10	P10	500	ROSETTE	135	135	135	135
	S11	P11	500	ROSETTE	45			45
	S12	P12	502	ROSETTE		INDIFFERENT	INDIFFERENT	
Plies Group.2	S13	CORE	503	ROSETTE		INDIFFERENT	INDIFFERENT	
Plies Group.3	S14	P13	500	ROSETTE	45	45	45	45
	S15	P14	500	ROSETTE	135	135	135	135
	S16	P15	500	ROSETTE	0	0	0	0
	S17	P16	500	ROSETTE	45	45		
	S18	P17	500	ROSETTE	90	90	90	90
	S19	P18	500	ROSETTE	135	135		
	S20	P19	500	ROSETTE	90	90		
	S21	P20	500	ROSETTE	0	0		
	S22	P21	500	ROSETTE	135	135		
	S23	P22	500	ROSETTE	90	90	90	90
	S24	P23	500	ROSETTE	45	45		
	S25	P24	500	ROSETTE	0	0	0	0
	S26	P25	500	ROSETTE	135	135	135	135
	S27	P26	500	ROSETTE	45	45	45	45
	S28	P27	501	ROSETTE	INDIFFERENT	INDIFFERENT	INDIFFERENT	INDIFFERENT

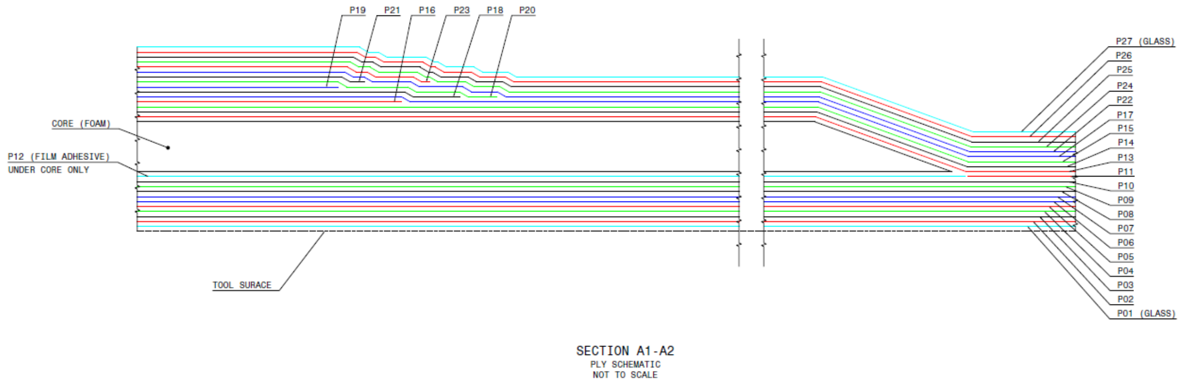


Figure 11: Example as-manufactured composite part definition

If we wish to represent this part, then at a minimum we need

Table 1: Minimum required geometry for the definition of a part

Item	Type	
Tool surface (base surface)	Geometry	Surface
Over-core surface (intermediate surface)	Geometry	Surface
Ply boundaries	Geometry	Line
Rosette/Layup axis	Geometry	Axis system
Ply thicknesses	Mapped property (See 3.4.4 Field mapped properties)	

And we may also include

Table 2: Additional geometry for the definition of a part

Item	Type	
Solid model of cured component	Geometry	Solid Body
Surface for base of each ply	Geometry	Surface
Top surface of part	Geometry	Surface

If we wish to define any tolerances on the part, or any features, then we may need to define more geometry to describe this

3.2.3 Other geometry not required for part definition

We may also define additional geometry, not necessary to define the part but necessary to define interfaces with the part and its parent assembly, or the part and its manufacturing processes.

- Reference points for referencing the part
- Engineering edge of part
- Manufacturing edge of part
- Axis systems

3.3 Materials

A constituent material, in the context of a composite part, is one of the constituent components from which the composite part is made.

Our composite part when cured will also have different material properties from its constituents, all of which we may want to track. This might be complex, where the material properties vary throughout the part as its architecture or processing treatment varies.

Typical materials include:

- Prepreg fabric
- Fabric
- Resin
- Core material (foam/aluminium/…)
- Adhesive layer

Note that fabrics in themselves are often complex, and to perform analysis we may need to know the ontology or architecture of these materials.

To add to the complexity: sometimes we will use two constituents as a single constituent *(e.g. dry fibre infusion vs. thermoset prepregs)*. We may also be making our own materials during the manufacturing process *(e.g. braided layers onto a mandrel are materials)*.

Note also that we may wish to simulate our component down to the sub-material level (i.e. modelling the architecture of the material) as a part of our process, so it is important that we can describe the material with a high degree of fidelity.

Figure 12: Examples of complex materials: Hexcel UD tape and Non-Crimp Fabric, and an Easy Composites braided sock

3.3.1 Fibrous materials & their properties

The ontology of a fibrous material (that is one that contains a fibrous phase, regardless of whether or not it is a prepreg containing a resin phase) consists of layers of sub-materials, potentially stitched together or held together with resin.

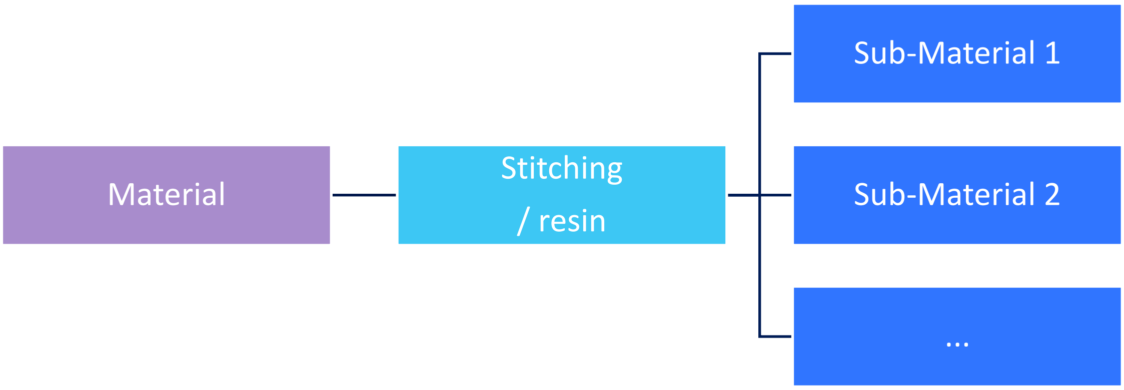


Figure 13: Ontology of a constituent fibrous material

Here is a list of properties associated with a fibrous material. In addition we need material traceability: to record a batch number from material roll, to each cut piece.

Table 3: Fibrous material properties

Property	Examples	Priority
Format	Thermoset prepreg slit tape	Desirable
	Thermoplastic prepreg slit tape	
	Ceramic prepreg towpreg	
	Dry fibre slit tape	
	Dry fibre tow tape	
	Non-crimp fabric	
	Woven fabric	
	Prepreg Ceramic slit tape	
Manufacturer		Essential
Product Short Name		Desirable
Product ID		Essential
Description		Essential

Fibre	Fibre Format		Sometimes
	Fibre manufacturer		Sometimes
	Fibre Name		Sometimes
	Fibre Size		Sometimes
	Fibre Properties	See many of the same properties as the composite part	Sometimes
Matrix	Matrix Type		Sometimes
	Matrix manufacturer		Sometimes
	Matrix viscosity – At 20°C	Sometimes	
	Matrix viscosity – profile	Sometimes	
Binder	Type		Sometimes
	Format		Sometimes
Toughening Veil	Type		Sometimes
	Format		Sometimes
Ontology / Architecture		[B, V, +45°, -45°, V]	Essential
Cured Ply Thickness [mm]			Essential
Width	Nominal width		Always
Weight	Material Areal Weight (MAW) [gsm]		Always
	Fibre Areal Weight (FAW) [gsm]		Sometimes
	Resin Areal Weight (RAW) [gsm]		Sometimes
Processing Window	Storage Lower Bound [°C]		Sometimes
	Storage Upper Bound [°C]		Sometimes
	Deposition Lower Bound [°C]		Sometimes
	Deposition Upper Bound [°C]		Sometimes
	Infusion Lower Bound [°C]		Sometimes
	Infusion Upper Bound [°C]		Sometimes
	Nominal Cure Profile [°C]		Sometimes
Minimum steering radius			Desirable
Permeability		K1, K2, K3	Desirable

3.3.2 Matrix materials & their properties

Resins are relatively simpler than fibrous materials. We do not need an ontology to describe them. Here is a list of properties we might wish to record for a resin.

Table 4: properties of a matrix material

Property		Examples	Priority
Format		Polyester (UPE)	Desirable
		Vinyl ester (VE)	
		1-part epoxy (EP)	
		2-part epoxy (EP)	
		Polyurethane (PU)	
Manufacturer			Essential
Product Short Name			Desirable
Product ID			Essential
Description			Essential
Density			Essential
Processing Window	Storage Lower Bound [°C]		Desirable

Property		Examples	Priority
	Storage Upper Bound [°C]		Desirable
	Infusion Lower Bound [°C]		Desirable
	Infusion Temperature Ti [°C]		Desirable
	Infusion Upper Bound [°C]		Desirable
	Nominal Cure Profile [°C]		Desirable
Viscosity	Viscosity at 20°C		Desirable
	Viscosity at Ti°C		Desirable
	Viscosity profile		Desirable
Cure	Cure profile…		Desirable

3.3.3 Other materials

We may need to define some other materials that are included within the part:

- Core materials
- Inserts
- Adhesive films
- Etc.

We have not listed any material properties for these non-composite specific materials, but specific properties may well be required to be known for simulation & maybe even for

3.4 Properties

3.4.1 A definition of properties, parameters, and variables

Formally, a property belongs to an object "the oven has a **maximum operating temperature of 250°C**", a parameter is an input to a method or process "set the oven to **220°C**", and a variable is a value capable of varying (can be an input or an output) of a method or process "Check the **actual temperature** of the oven".

We will use property to be a value belonging to the composite part or item in the part tree that does not vary during manufacture, and variable to describe a value that does, while parameter will be for values that are inputs to the process and therefore should not crop up often in our description of a part – unless we wish to record the original design parameters for the part (we don't).

Note that all measured or simulated properties have uncertainty, only design nominal data does not. We may wish to record the sources and uncertainty of properties. e.g. part mass is 100±5g measured by scales with ID 12345.

3.4.2 Discrete properties

Discrete properties have a single value and belong to some item in the part tree, *examples include:*

- part properties such as the mass of the part (See 3.4.2 Discrete properties)
- ply properties such as the nominal orientation of the fibres in a ply,
- material properties such as fibre areal weight.

3.4.3 List of composite part properties

Below is a list of properties that we might want to record about a composite part. The priority column is indicative only, and in fact any property used to validate that the part meets its specification is essential.

Note that many of the composite part properties can be described as a field property.

Table 5: list of composite part properties

Property		# dims	Priority
Density	ρ	1	Essential
Fibre Volume Fraction	Vf	1	Essential
Poisson's ratio	ν12, ν13, ν23	1	Essential
Shear Modulus	G12, G23, G31	1	Essential
Tensile modulus	E11T, E22T	1	Essential
Tensile strength	S11T, S22T	1	Essential
Tensile strain at break		1	Essential
Flexural modulus		1	Essential
Flexural strength		1	Essential
Compressive modulus	E11C, E22C	1	Essential
Compressive strength	S11C, S22C	1	Essential
Interlamina Shear strength	S23	1	Essential
Coefficient of thermal expansion	α1, α2, α3	1	Essential
Coefficient of moisture expansion		1	Desirable
Melt Temperature	Tm	1	Desirable
Glass Transition Temperature	Tg	1	Desirable
Through thickness tensile strength		1	Desirable
Through thickness compressive strength		1	Recommended
Compression after impact strength		1	Recommended
Filled hole compressive strength		1	Recommended
Open hole tensile strength		1	Recommended
Filled hole tensile strength		1	Desirable
Open hole compressive strength		1	Desirable
Bolt bearing strength		1	Desirable
Mode I interlaminar fracture toughness		1	Desirable
Mode II interlaminar fracture toughness		1	Desirable
Mixed mode fracture toughness		1	Desirable

3.4.4 Field mapped properties

We must often map part properties to the part geometry, where those properties are continually varying field variables.

Example: the thickness of a laminate could be described as a single value, nominal thickness or actual (average) thickness, but if we want to be able to asses thickness against a tolerance or to use higher fidelity thickness data in analysis, we must create a map of the property on the part.

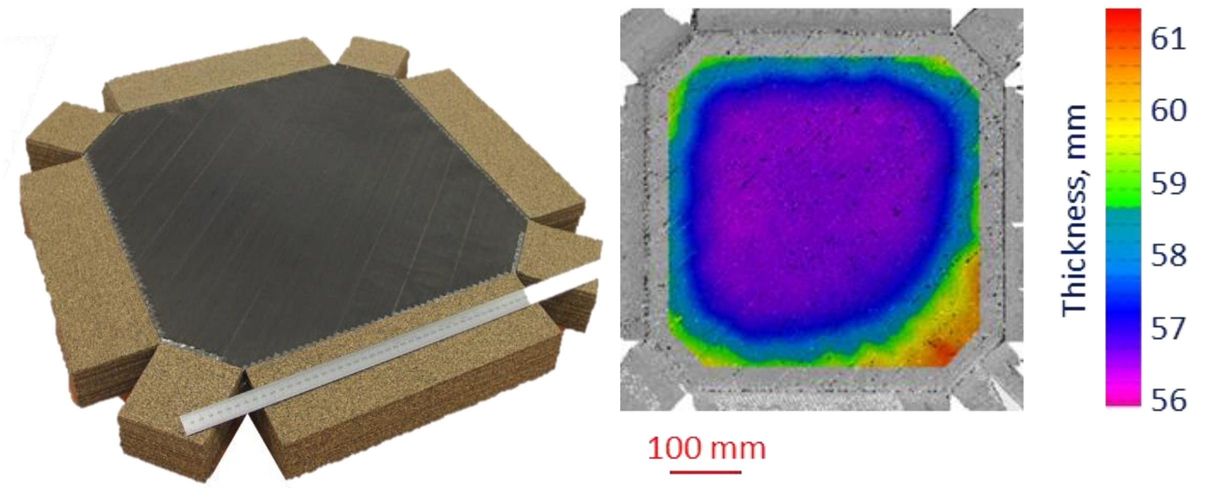


Figure 14: A thick stack laminate and its corresponding mapped thickness

Table 6: list of mapped properties

Property		**#dims**	**Can be mapped, can be expressed as geometry?**
Thickness or bulk		1	Map
z-height (of ply above base surface)		1	Map or geometry
Normal *(of ply element/node translated by z-height, this is a CAD thing, where we only wish to save one copy of the underlying mesh)*		3	Map only
Degree of curvature (of surface, related to : radii),		1	Map only
Fibre orientation (field of single values)		1	Map only
Fibre orientations (field of Warp, Weft, Axial values)		3	Map only
Fibre distributions (field of vectors)		3	Map only
Shear angle		1	Map only
Steering angle		1	Map only
Porosity		1	Map only
US transmission rate		1 or more	Map only
Binder coverage		1	Map only
Veil coverage		1	Map only
Roughness		1	Map only
Residual stress		1 or 3	Map only
Spring back	As a z-offset	1	Map or geometry
	Angle between surfaces	1	Map

3.4.5 Property sources

A manufactured composite part is never an exact match to the nominal part designed. In some cases, we could obtain a closer representation of the part by simulation of part & process and use that as our definition for evaluation of part compliance with requirements/tolerances.

E.g. we might simulate forming, giving us a better description of the fibre angles likely to be present on the tool during manufacture, perform structure analysis on this, accept the result as meeting the part *specification, and then want to use the forming simulation results as a field property to which to inspect rather than the discrete CAD nominal fibre direction.*

When we write programs for automation to manufacture the part, we often add detail about the part that was previously not recorded.

e.g. when we program an AFP job, the ply shapes come from design, but we are discretising these into a series of tows (AKA tapes) during programming. We might want to retain and differentiate the CAD nominal ply single piece and the programmed tapes as pieces, especially if our CAD nominal has any attached tolerances.

We therefore need a method for describing what source system a property of the part comes from, so that we can choose to inspect or analyse against it.

Figure 15: Example of a composite part development process

3.5 Features

We may wish to define a zone of our part for a couple of reasons: we may wish to apply a tolerance to only a specific zone, or we may wish to record the location of a feature for later analysis *(e.g. we may wish to record the location (and properties) of each ramped section in a part, so that we can analyse to understand if ramps had an effect on part quality.*

Features and zones can be seen to be akin to a mapped property in that they have exist in some mappable location on the part, so that you could create a binary map of the part indicating which locations belong to a particular type of feature (or, as with some of the properties, the zones can be defined with geometry)

3.5.1 Composite features

Here is a list of composite features (features that we might wish to track in a composite part because they have an effect on manufacturability):

- Holes
- Ramps
- IML face
- Datum / Reference face for spring back calculation
- OML face
- Edges
- Convex radii
- Concave radii
- Over core plies
- Add
- Cut
- Within x mm of any of the above features

3.5.2 Zones

There are no default zones that would always or usually be included within the definition of a part. Zones are usually required for applying tolerancing, these are often applied to many of the same features as in the Composite Features list.

- Grade A/B/C surfaces

3.6 Tolerances

There is no standardisation around the way that we write tolerances for composite parts, except where those tolerances are GD&T type tolerances, so we cannot adopt an existing standard that will cover everything we need here. We have therefore created a standard to support this work. See NCC-TEC-4467 Standard for Composite Part Tolerancing.

For GD&T tolerances we may wish to comply with an existing standard such as ISO Geometrical Product Specifications (GPS) or ASME Y14.3 and implement this in our Model in compliance with the STEP AP203 or AP242 or the QIF standard.

Tolerances are commonly placed against the following inspection items:

Table 7: Table of inspection items and their properties

#	Category	Type	Properties
1	Material Properties	Fibre areal weight	mass, area
2		Fibre direction (in plane)	orientation
3		Shear angle	angle
4		Steer angle	angle
5		Glass transition temperature	temperature
6		Thickness	same as bulk
7		Splice	Quantity
8		Fold	Quantity
9		Twist	Quantity
10		Wrinkle	height
11		Mass	mass
12		Fibre volume fraction	percentage, mass
13	Fabric Damage	Discontinuity: Tow	quantity
14		Discontinuity: Stitching	area
15		Discontinuity: Binder	area
16		Discontinuity: Veil	area
17		Fibre gap	width
18		Fray	length, width
19		Tear	length
20		Cut	length
21		Dart	length
22		Scorch	length
23	Voids & Inclusions	Foreign Object Debris	area
24		Fuzz	area

#	Category	Type	Properties
25		Depression	quantity, diameter
26		Protuberance	diameter, length, quantity
27		Contamination	area
28		Internal void	volume
29		Porosity: Volume	volume
30		Porosity: Layer	depth, quantity, length, surface area, area
31		Starvation: Resin	area
32		Starvation: Fibre	width
33	Laminate Damage	Disbond	area
34		Delamination	length, width, area
35		Matrix crack	area
36		Fibre and matrix crack	area
37		Scratches	depth
38		Flaking	area
39	Material Geometric	Piece shape	length, width
40		Boundary position	position
41		Piece to piece distance	width, length, quantity
42		Bulk	thickness
43		Bridging	radius
44		Sharp edges	length
45		Flash present	area
46	GD&T	Profile of a Surface	surface profile
47		Surface roughness	roughness
48		Dimension	length, width, height, thickness
49		Parallelism	surface profile
50		Perpendicularity	surface profile
51		Curvature	surface profile
52		Flatness	surface profile
53		Hole diameter	diameter
54		Hole position	position
55		…	mass, area

We have developed a standard methodology with the definition of tolerances that is compatible with Model Based Definitions, and for the quantification of these items including standardisation of how to measure each parameter.

Here is an example of a tolerance definition using the definition methodology laid out in See NCC-TEC-4467 Standard for Composite Part Tolerancing.

This is a porosity tolerance attached to the “Top Surface” of a part (a zone that would be defined in the model), and, line by line:

1. it is filtered to only apply to porosity with pore depths > 0.5mm, and
2. There must not be more than 15 pores per cm^2 in the affected zone
3. The affected zone must not be longer than 200mm

4. No pore deeper than 10.mm
5. The total of all affected zones must not sum to more than 4% the “Top Surface” area.

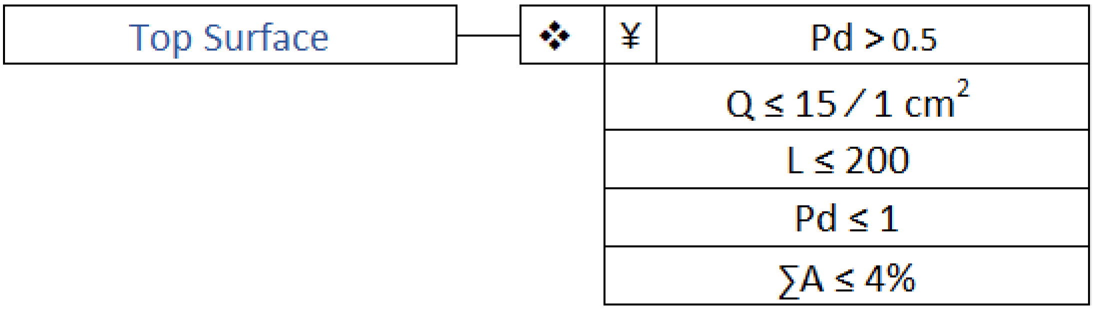


Figure 16: example of a porosity tolerance,
see NCC-TEC-4467 Standard for Composite Part Tolerancing

Of course, this definition presupposes that we have a standard definition for zones of porosity, this is included in the referenced specification.

Reproduced from 5.2 Out-of-tolerance item:

When we return from the concessions process, we record a result against that out of tolerance item. The returned instructions may give some specific details about how to rework the part to achieve compliance to a more relaxed tolerance than that in the definition of the part. This is recorded in the definition, along with the limits of its scope.

3.7 Part configurations

For the purposes of this document, we will say that a part has one complete definition, which may consist of one or more configurations (each of these can define new geometry and ontology)

We may wish to define the different shapes and ontologies of the composite part at these various stages of manufacture, in order that we can run our manufacturing & QA processes against each of those configurations. And since the part is transformed many times during manufacture we may wish to track the parameters of the raw input material right through into the final part (e.g. defects present in the material roll should be tracked and located within the final delivered part).

We therefore need to be able to add configurations of the component at various stages of manufacture.

Figure 17: Simple example composite part manufacturing process

4 As-Manufactured definition

Composites manufacture is an additive, transformative, and a subtractive process; the constituent parts are being combined and altered throughout the process.

4.1 Manufacturing status

The as-manufactured part description could have the capacity to record the current state of build, which includes a record of which pieces are present in the part. It does not have to record how the build is performed, that is for the process twin.

Each piece of the build may be reworked or replaced, we need a method for recording the data about the original attempts for our later analysis and the data about the replacement or reworked piece.

The statuses for the pieces and the part could be derived from the stages of manufacture, but with some additions (which could be included in the stages of manufacture by default):

- Not started
- *{stages of manufacture}*
- Reworked
- Scrapped
- Complete

4.2 Composites Inspection

We require a way of recording the actual condition of the part that we are making. There are two topics to consider: the geometric condition of the part or items of the part, and the defects present within it.

4.2.1 Defect condition

We require to track the following defects within the part. The means of determining their properties is described in See NCC-TEC-4467 Standard for Composite Part Tolerancing.

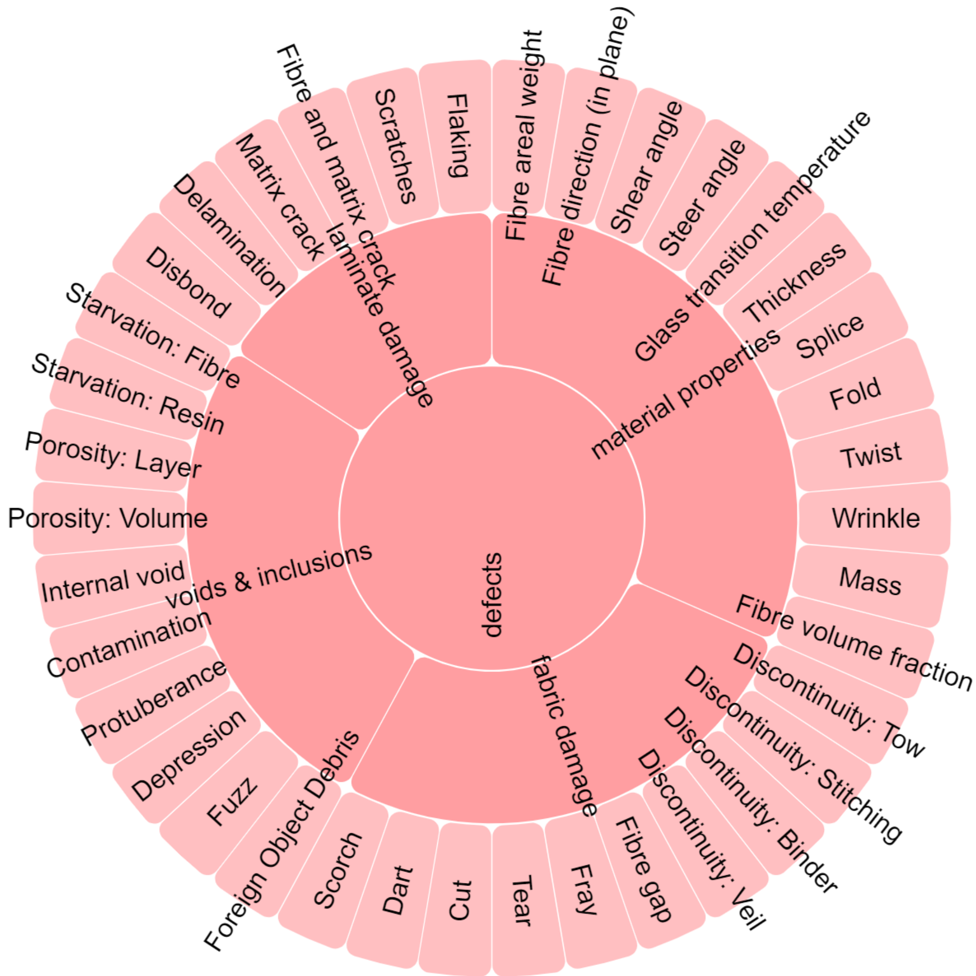


Figure 18: ontology of composite defects

Table section reproduced from 3.6 Tolerances.

#	Category	Type	Properties
1	Material Properties	Fibre areal weight	mass, area
2		Fibre direction (in plane)	orientation
3		Shear angle	angle
4		Steer angle	angle
5		Glass transition temperature	temperature
6		Thickness	same as bulk
7		Splice	Quantity
8		Fold	Quantity
9		Twist	Quantity
10		Wrinkle	height
11		Mass	mass
12		Fibre volume fraction	percentage, mass
13	Fabric Damage	Discontinuity: Tow	quantity

#	Category	Type	Properties
14		Discontinuity: Stitching	area
15		Discontinuity: Binder	area
16		Discontinuity: Veil	area
17		Fibre gap	width
18		Fray	length, width
19		Tear	length
20		Cut	length
21		Dart	length
22		Scorch	length
23	Voids & Inclusions	Foreign Object Debris	area
24		Fuzz	area
25		Depression	quantity, diameter
26		Protuberance	diameter, length, quantity
27		Contamination	area
28		Internal void	volume
29		Porosity: Volume	volume
30		Porosity: Layer	depth, quantity, length, surface area, area
31		Starvation: Resin	area
32		Starvation: Fibre	width
33	Laminate Damage	Disbond	area
34		Delamination	length, width, area
35		Matrix crack	area
36		Fibre and matrix crack	area
37		Scratches	depth
38		Flaking	area

4.2.2 Geometric condition

We wish to record the conditions of the following geometric conditions of the part:

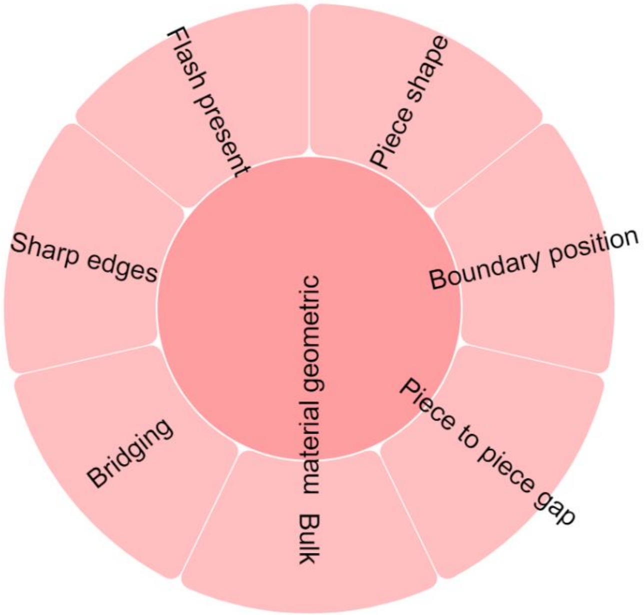


Figure 19: material geometric inspection

Table section reproduced from 3.6 Tolerances.

#	Category	Type	Properties
39	Material Geometric	Piece shape	length, width
40		Boundary position	position
41		Piece to piece distance	width, length, quantity
42		Bulk	thickness
43		Bridging	radius
44		Sharp edges	length
45		Flash present	area

Each item or feature described must be tagged with the property source (3.4.5 Property sources) and stage of manufacture (3.7 Part configurations).

e.g. if we inspect a ply shape on the tool during the deposition activity we need to tag that data as "As-Manufactured" data taken at the "Deposition" stage.

Piece to piece distance is an interesting inspection item as it requires to measure the gap between two pieces. Where should this be mapped to? Or should it be created as geometry in its own right? Given that a tolerance on such a gap would be something like 0.5±0.5mm, this would be more easily compared to a map.

4.3 GD&T inspection

We require to inspect against any of the GD&T tolerances. See the discussion on GD&T tolerances in 3.6 Tolerances.

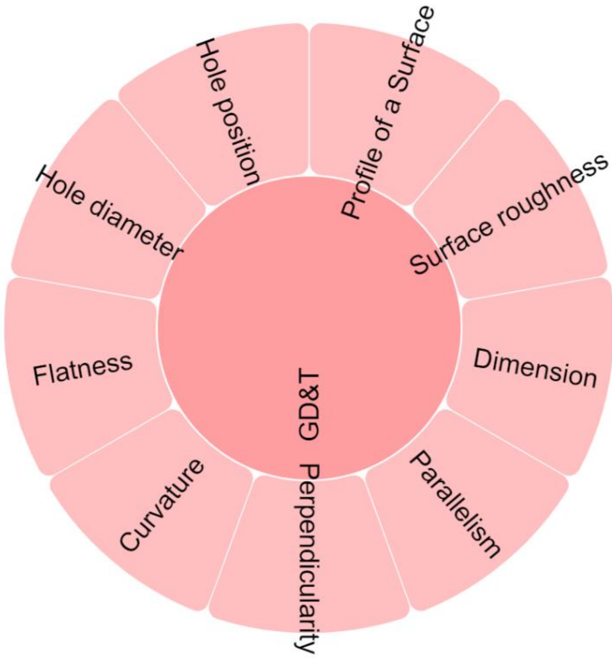


Figure 20: material GD&T inspection

Table section reproduced from 3.6 Tolerances Error! Reference source not found..

#	Category	Type	Properties
46	GD&T	Profile of a Surface	surface profile
47		Surface roughness	roughness
48		Dimension	length, width, height, thickness
49		Parallelism	surface profile
50		Perpendicularity	surface profile
51		Curvature	surface profile
52		Flatness	surface profile
53		Hole diameter	diameter
54		Hole position	position
…		…	

4.3.1 Transformation of inspected items

There are two scenarios in which we require to be able to transform inspection data:

1. When the shape of the part is modified by a manufacturing process
2. When we know more accurate information about the location of the part or items within it.

While the data format itself will not be responsible for performing the transformations (that would be the responsibility of the applications that manipulate the data), **the format does need to be able record that these are all instances of the same defect**.

4.3.2 Transformations due to manufacturing process

Take an example *(illustrated below) of a roll of material with a non-critical defect that we wish to track, the defect starts in the roll, must be transformed into the cut piece given information about the nest, and then must be transformed again into the formed part following the transformation of 2D to 3D ply. This gives us the location of the defect in the final part.*

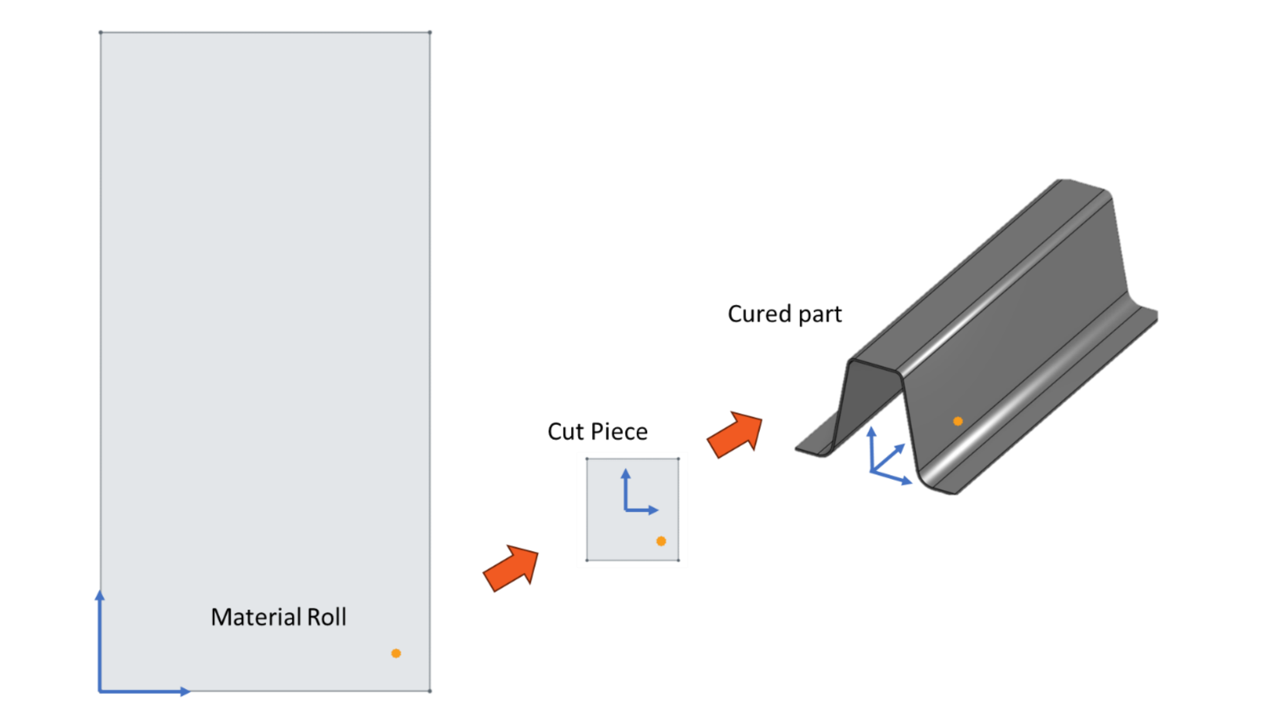


Figure 21: Example of transformation of a defect feature throughout manufacture.

4.3.3 Transformations due to inspection process

In item 2, if we measure the location of a defect in tool coordinates and translate this into piece coordinates when creating the defect feature, then later we measure the location of the piece to be Δmm out of position (where Δ is a vector for our positional error), then we must transform the location of the defect in piece coordinates by the inverse of Δ in order that it remain in the same location in the model as in real life. This is illustrated below:

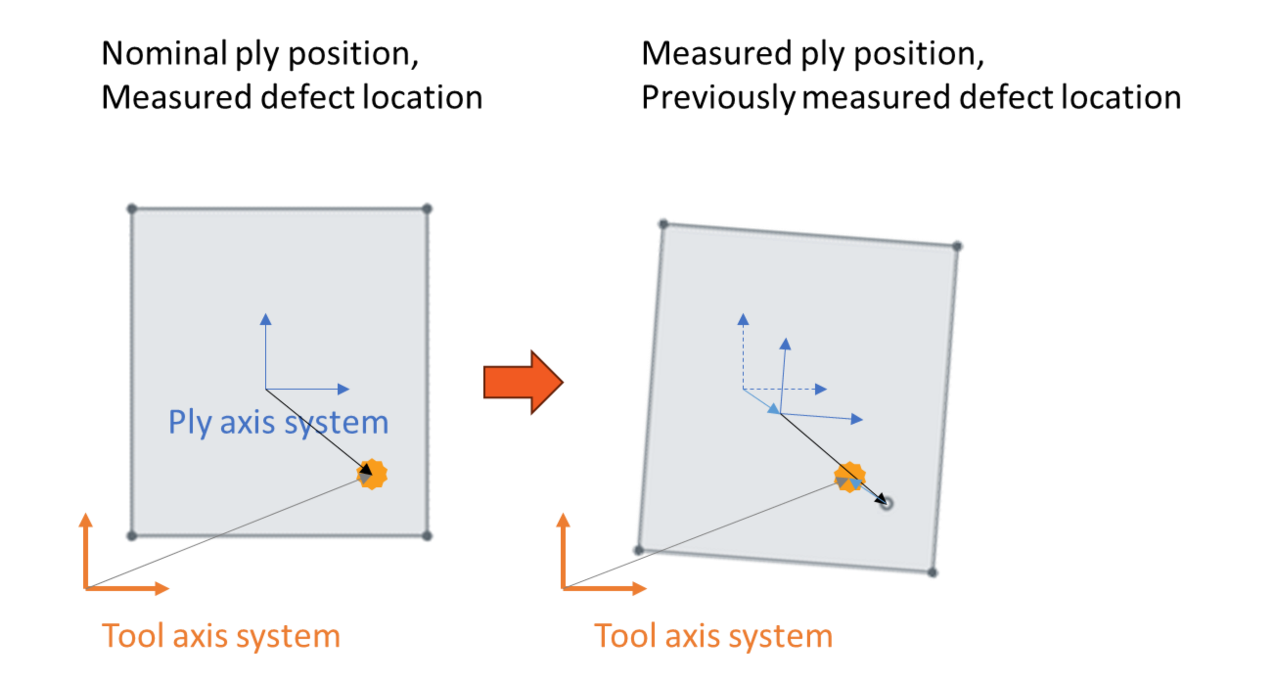


Figure 22: Transformation of a defect required when updating information about piece actual location

Of course, if we have measured the location of the defect in piece axis coordinates then we do not need to transform its location in piece coordinates when we update the piece location (the location of the defect will actually change in tool coordinate space). *e.g. a defect identified on the ply when it was sitting on the ply cutter bed will remain in the same relative location on that ply regardless of the position or drape of that ply).*

5 Quality Assurance

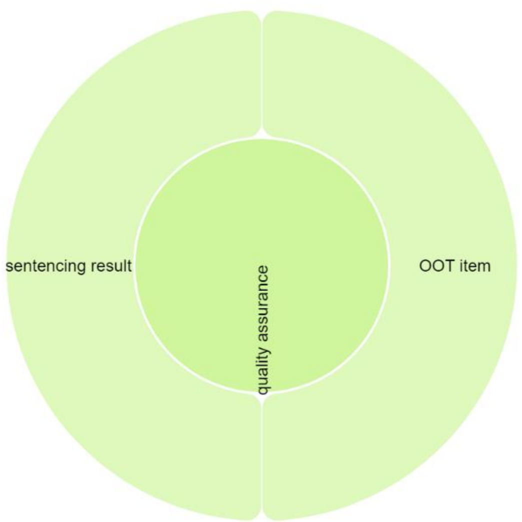


Figure 23: ontology of Quality Assurance

5.1 Sentencing result

We evaluate each of the tolerance items that have a bearing on each defect in turn after adding that defect or a series of defects to determine if any of those tolerances have been broken. Once complete we obtain a sentencing result which we record against the defect:

- In tolerance
- Out of tolerance

Some tolerances evaluate a limit of the quantity of a certain defect within a search distance or area, or a sum total area of defect regions in a particular zone. This means that by adding one defect to a list of defects we can cause others to move to “In tolerance” to “Out of tolerance”. Plus we want to be able to handle out of tolerance items as single entities: so it may be bests to view these as raised against the tolerance and including references to each contributing defect.

5.2 Out-of-tolerance item

We then make a decision about the out of tolerance (AKA non-conforming) items:

Table 8: Possible decision outcomes for an out-of-tolerance item

#	Decision	Concession required?
1	Rework the item affected	No
2	Scrap and replace the part	No
3	Request to use the product as is	Yes
4	Request to repair the non-conformance	Yes

If we choose items 3 or 4, we must send a concessions form from supplier to customer. A third-party app is responsible for the concessions process and any data required from the part and process digital twins. We therefore need a reference ID for the feature or item involved in the concession.

When we return from the concessions process, we record a result against that out of tolerance item. The returned instructions may give some specific details about how to rework the part to achieve compliance to a more relaxed tolerance than that in the definition of the part. This is recorded in the definition, along with the limits of its scope.

5.3 Reworked item

Reworking of out of tolerance items is covered under **4.1 Manufacturing status, reproduced here** for clarity:

Each piece of the build may be reworked or replaced, we need a method for recording the data about the original attempts for our later analysis and the data about the replacement or reworked piece.

6 Traceability

6.1 Versioning

Versioning of the data must be mindful of the fact that the data will be stored in a database in files/tables that don't necessarily maintain the data in a contiguous lump. So it is not a single file that can be given a version number, rather the data structure must support versioning.

In manufacturing environments there will be a great many parts made to a single definition of a part, so an efficient data format will allow for many as-manufactured parts to reference one part definition, adding additional information including definitions esp. of tolerances as they are required, without breaking the original definition so that it still works for all the other part data.

Database and/or third-party app design will allow for a versioning workflow that makes read-only any released part definitions.

6.2 Event logging

To provide traceability, every action or decision that updates the condition of the part is logged. The data included in the log includes:

- The date and time
- The username or system name if automated
- The software vendor, name, and version
- Any relevant system parameters/properties/variables
    - e.g. Temperature (for measurement systems)
- The affected items
- A description of the event

6.3 Referencing

We require to reference any item in the part ontology tree, any geometry, any feature including tolerances, inspection items, out-of-tolerance items, events, and materials.

6.4 Uncertainty

With any measurement there exists a degree of uncertainty, we may wish to record that uncertainty along with any dataset (whether they are actual values measured with some metrology device, or simulated). While we could include all the measurement system variables along with the associated event, there is an argument to included them instead along with the dataset, at least where they are parameters that contribute to uncertainty.

6.5 Measurement units

It would be impossible to properly interpret any of the data stored unless we were able to define the measurement units used. Since this data format is intended for use in a distributed database we propose that any record set include the measurement units with it.

7 Requirements

7.1 Prioritisation for the previously defined

7.1.1 Each requirement marked Essential in the table below must be included in the data format Minimum Viable Product (MVP).

7.1.2 Each requirement marked Recommended in the table below should be included in the data format MVP.

7.1.3 Each requirement marked Desirable in the table below could be included in the data format MVP.

Section	Requirement	Priority for the MVP
4 Nominal definition		
4.1 Layup ontology		
	Describe the layup ontology of a composite part	Essential
4.2 Geometry		
	Describe the geometry of a composite part	Essential
	Allow for assignment of geometry to any part of the ontology of the composite part	Essential
4.3 Materials		
	Describe materials	Essential
	Allow for referencing of material associated to a ply or cut piece	Essential
	Allow for discrete properties associated to materials	Essential
	Contain predefined discrete properties (those marked as priority Essential)	Desirable
4.4 Properties		
	Allow for discrete properties to be defined against any item in the ontology	Essential
	Differentiate properties by data source	Recommended
	Contain predefined discrete properties for a part (those marked as priority Essential)	Desirable
4.5 Features		
	Allow for definition of zones	Recommended
	Allow for definition of composite features	Desirable
4.6 Tolerances		
	Allow for definition of generic composite tolerances	Essential
	Allow for definition of composite tolerances as per NCC-TEC-4467 Standard for Composite Part Tolerancing	Desirable
	Allow for definition of any GD&T tolerance	Essential
4.7 Part configurations		
	Allow for multiple part configurations	Desirable

Section	Requirement	Priority for the MVP
5 As-Manufactured definition		
5.1 Manufacturing status		
	Allow for recording a status against any item in the part ontology	Desirable
	Include a reworked status option (6.3 Reworked Item)	Desirable
5.2 Composites Inspection		
	Allow for definition of the defect condition of the part	Essential
	Allow for definition of the geometric condition of the part	Essential
5.3 GD&T inspection		
	Allow for the definition of the inspected condition of the part	Essential
5.4 Transformation of inspected items		
	Allow for x-referencing inspected conditions and items that are transformations of each other	Desirable
6 Quality Assurance		
6.1 Sentencing result		
	Allow for definition of sentencing results	Recommended
6.2 Out-of-tolerance item		
	Allow to record a concessions result against an out of tolerance item	Recommended
7 Traceability		
7.1 Versioning		
	Allow for versioning of the data in a granular way suitable for databased data	Recommended
7.2 Event logging		
	Allow for definition of an event log, with the parameters described	Recommended
7.3 Referencing		
	Define references for any item in the part ontology tree, any geometry, any feature including tolerances, inspection items, out-of-tolerance items, events, and materials.	Essential
7.4 Uncertainty		
	Add an uncertainty value as a parameter to a dataset	Desirable
7.5 Measurement units		
	Define measurement units for each dataset / data individually	Recommended

7.2 Data access, filetypes, portability

The data format

7.2.1 Must be publicly released under an open source licence *(e.g. the MIT licence)*

7.2.2 Should be compatible with a databased structure.

7.2.3 Should be fast to read and write
This might mean selecting an open source binary file format at least for the larger geometrical definitions and data mappings.

Appendices and annexes

Software list – non-exhaustive

- Concept design
  - CATIA V5
  - 3DX
  - Siemens NX
  - Siemens Teamcenter
  - Solidworks
- Simulation
  - ANSYS
  - ABAQUS
  - HypoDrape
  - Pam-Composites
  - MSC Apex
  - MSC Nastran
  - Digimat
  - LMAT
  - Moldex3D
  - LIMS
  - Polyworx
  - Altair HyperWorks
- Process Design
  - Word (Instruction sheets are written in Word documents)
  - Microsoft D365
- Programming
  - Coriolis CATFibre, CADFibre
  - Simulia, Delmia

  - CADWind
  - CADFil
  - CGTech vericut pro
  - Loop Technology FibreDRIVE
  - RobotStudio
- Manufacture
  - PolyWorks
  - PolyWorks Loop
  - (Spatial Analyzer)
  - Profactor software
- Data Analysis
  - Python
  - PowerBI