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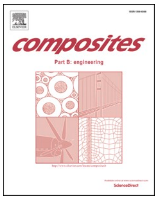

Features and defects characterisation for virtual verification and certification of composites: A review

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ABSTRACT

Composite manufacturing is driven by a balance between costs (i.e. material and time) and quality. Due to the brittle nature of composite materials, even small deviations in the parts (i.e. defects) can result in significant reductions in load carrying ability of a part. The occurrence of defects is a complex problem, with many sources and factors which affect them. To assist in better understanding and predicting part quality, statistical tools and advanced machine learning can be used to help fill the gaps. A solid understanding of part quality can then in turn be used in combination with a digital twin to achieve virtual testing and certifcation of a part while requiring less physical tests. However, as this review shows, the available data in the literature does not sufficiently characterise key defects, nor their dependence on part design and process parameters to achieve this goal. As such it is argued here that enhanced characterisation and manufacturing trials of more complex parts are needed to generate the required database.

1. Introduction

The drive for improved part efficiency, both from a cost and environmental standpoint, has long driven research into the manufacturing of composite components and the occurrence of defects. However, as the extensive taxonomy for autoclave and resin transfer moulding (RTM) presented by Potter [1] clearly demonstrates, the factors influencing part quality and variability stem from every stage of manufacturing—from generating the raw materials and preforms to finishing and assembly—and every parameter controlling each of these stages can be influential, including system parameters such as cure temperature and pressure, as well as less traceable and quantifiable parameters surrounding the human handling in any stage (e.g. whether the technician doing manual deposition of plies was left handed or right handed). Tackling such a wide range of issues is prohibitively complex and expensive, and as a result the literature has instead delivered many targeted studies that dig deep into a single parameter or a subset of parameters within a selected stage of the production of a certain component using a selected manufacturing technology.

Recently, the introduction of artificial intelligence (AI) and advanced statistical techniques into the composite manufacturing and analysis space have allowed gaps in knowledge to be overcome and existing models to be leveraged to achieve previously prohibitively time and cost intensive activities. For example, machine learning (ML) neural networks (NN) were trained on numerical models of an autoclave by Humfeld et al. to allow it to detect deviations in the temperature profile in a part and compute in-situ correction of the autoclave set-points to achieve the desired temperature profile in the actual part [2]. A related study by Szarski and Chauhan used deep learning algorithms trained on cure simulation data from a 1D model to create an adaptive oven controller that was used in a Bayesian optimization loop to optimize the tooling mass distribution and target air temperature profile to reduce ramp times by up to 40% [3].

On the design and analysis side, Furtado et al., following an earlier study by Vallmajó et al. [4], have published a study looking at different machining learning algorithms and their ability to predict notched strength of composite laminates as a method for determining design allowables for previously untested laminates without requiring expensive testing or simulations [5]. Of special interest in the current paper is the Bayesian framework put forward by Sandhu et al. for the determination of bending strength and its distribution for a corner piece containing a wrinkle [6]. This study used scan data from several corner pieces cut out of C-sections to establish a basis for the occurrence of the wrinkles and their variation in these parts. This was then coupled with a high-fidelity 3D model to compute the bend strength and the possible distribution of bend strength for the possible variations of wrinkles.

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These types of advancements bring the promise of using digital twins along with AI/ML and statistical tools to enable digital certification of composite parts with significant testing replaced with these novel technologies. This vision requires connecting historical data with state-of-the-art NDT data and high-fidelity numerical models to complete the performance predictions. The historical data serves to provide a broad basis for establishing the baseline probabilities while the new NDT data is used to better understand the specific part and update the baseline probabilities through Bayesian Learning (BL). Recently, the literature has seen examples of tools developed to directly utilise high resolution NDT scan data to generate meshes for numerical models [7], side-stepping any need to characterise the meso-structure and extract metrics on any defects. However, in order to leverage the historical data within a BL process, characterisation of the material volume is needed to understand what is contained within and how this might vary from one copy of the part to the next.

Digitalisation technologies have a wide range of potential impacts, as they can be deployed for any composite part. The additional quality control and insight offered by deploying these technologies is likely to add significant value to more safety and weight critical aerospace applications, including commercial aviation and unmanned aerial vehicles as well as emerging markets such as electric vehicles, urban/private aircraft, and vertical take-off and landing vehicles.

In this review, the focus is specifically on defect characterisation from the perspective of digital verification and certification of composite parts. As such the targeted form of digitalisation is that of a manufacturing process digital twin, which could be used to ensure part quality in serial production. Hence the literature is reviewed and missing metrics, needed to recreate key features and defects will be identified. This review was carried out as part of the development of a database within the CerTest Programme [8]. First, the nature of what makes a feature and what makes a defect is explored and an updated taxonomy approach is proposed from the viewpoint of building a composites features and defects database that can be used for Bayesian Learning. Second, the current characterisation of key defect types and established trends in the data are reviewed, followed by a proposal for how characterisation of each defect type could be expanded to better capture realistic defects and support the drive towards more widespread use of Machine Learning in composites design. Finally, some conclusions are provided and the overall way forward as seen by the authors is given.

2. Features vs. defects

In order to properly define the total class of “defects”, it is important to establish the criteria by which such features can be distinguished from the totality of all possible mesoscopic and microscopic features. This starts by establishing a baseline from which deviations can be identified, which can be either a “pristine” component or alternatively an “as-designed” component as the case may be. Within the standard testing and development pyramid approach, this would be the flat coupon specimens which are broadly used to characterise the physical and mechanical properties of the base composite material systems. However, some features not present in flat coupons can nonetheless also be considered “baseline”. A great example to highlight this are resin pockets that occur in parts containing ply drops and use traditional ply deposition methods, where resin pockets are inherent to the part as-designed. Ply drops and tapered laminates have been studied extensively [9,10] with several studies outlining guidelines to maximise performance [11–13], and recent studies continuing to demonstrate the importance of correctly selecting the ply drop schedule [13]. However, it can readily be argued that the resin pockets, at least for current manufacturing approaches which do not include ply chamfering, are the baseline and the only true “defects” are voids and potentially wrinkling and waviness that are induced by dropping plies [14].

The second step in cordoning of “defects” is to address their identification. Generally, “defects” are flagged in the finished part, though defect precursors can often be observed during other stages of the manufacturing process. Hence, further distinctions can be made by evaluating the source of any variability. The entire manufacturing process can be broadly simplified into 5 stages:

1. Raw material production (e.g. fibres, tows, fabrics, prepregs)
2. Preform prep/handling (e.g. cutting, preforming, resin mixing)
3. Ply deposition
4. Moulding (e.g. curing, infusion for non-prepreg processes)
5. De-moulding, trimming and finish machining

Beginning at the first stage, Potter et al. [15] captured the innate variability of fibre and resin content in a unidirectional carbon fibre prepreg within the context of the specs and limits set by the manufacturers. While variability in the raw materials will translate to variability in the finished parts in the form of local variations, these same local variations are present in the coupons and hence captured implicitly within the spread of properties as observed in the coupon tests and hence only features in excess of this baseline of variability ought to be considered as defects. Furthermore, the focus can therefore also be limited to the final four stages, all of which will be influenced by the design of the part and have associated parameters that could influence the quality. A special note here needs to be made regarding the coverage in the literature on the final stage; demoulding, trimming and finish machining. Due to the manual nature of this stage, it is potentially a huge source of variability in the form of introduction of damage into the final part before it enters operation. However, due to the poor coverage in the literature, it is not considered in the rest of this review, but the authors stress the importance of it as a potential source of variability nonetheless.

The final key defining factor of “defects”, as considered in this work, is the knockdown they pose to the local material properties relative to those measured by coupon testing and/or their tendency to result in a component that is out of the bounds of specification (e.g. exceed certain geometrical tolerances). The specifications and performance knockdowns are key figures used in the concession process [16], and hence determine the significance of any given “defect”. Literature has well documented the influence on performance of the commonly studied defects including voids [17] and fibre wrinkling and waviness [18], however there is limited data on the actual occurrences of these “defects” in industrial parts, with rare examples either showing severity (e.g. fibre waviness maximum angle [19,20]) comparable to the levels established to exist in stock material [15] or showing development parts containing such severe defects they would never enter service. As such the open question remains: what mesoscopic and microscopic features are present in composite parts in serial production, what is their variability, and how do they influence performance?

This touches on a deeper question regarding industrial development and production practices. By the time a part goes into serial production, many production line improvements in the form of design changes and manufacturing process adjustments may have taken place. Furthermore, production line improvements are often carried out as a continuous effort to leverage the ever-growing information and experience, allowing for further reductions in part repair and scrap rates. On the other hand, the increased production scale and rate of parts in serialised production can also lead to increased variability as additional teams and suppliers are brought on board. This idea, that variability and quality potentially oscillate over time is traditionally not accounted for in the certification process, and in fact certification generally operates on the assumption that quality is consistent. However, if digital twin technologies are to be leveraged in a digital certification process, this phenomena and full effects of reducing the number of test coupons in exchange for numerical assessments needs to be directly considered and addressed.

The viability of digital twin technologies is also linked to the ability to inspect parts and extract the required descriptions of the mesostructural features. To this end, the capabilities of NDT are both a facilitating and potentially limiting factor. While use of NDT for compliance control has been well established for many decades [21], limitations in the speed, resolution, and scalability of various NDT techniques is an existing hurdle to easy integration into commercial activities. It is likely that full inspection of a part would involve multiple NDT techniques and rely on data fusion to get the best results [22]. The limitations of NDT techniques also acts as a scale limit on what can effectively be accounted for as a defect, since defects too small to be detected will simply be missing from all datasets. While influence of microscopic variations on macroscopic properties has been well demonstrated numerically [23], gathering the required data to effectively determine the possible variations, how they relate to baseline microscopic features in "pristine" laminates, and then set the bounds of the statistical analysis is prohibitive for these scale of "defects". As such, the studied defects in this review are limited to the mesoscopic (i.e. ply level) and macroscopic (i.e. part level) range, where detection is easier and the data more plentiful.

Given all the above considerations, the authors propose the following framework for understanding and further investigation of "defects" for the purpose of digital certification. It begins with the following definition of *defects* as: unwanted mesoscopic and macroscopic features, reliably detectable with available NDT technologies at industrial scales, whose occurrence and characteristics (e.g. size, location, severity) can be influenced through variations in design or tuneable process parameters (i.e. they are not found, or are of a much lower severity, in standard test coupons). Inherent in this definition is the notion that the set of defects is process dependent. This can also be observed from comparing the previous efforts of Potter who created an extensive taxonomy for autoclave prepreg and resin transfer moulding (RTM) [1], the work by Harik et al. who put together a set of defect cards for automated fibre placement [24], the reviews by Hassan et al. that looked at the parameters influencing defects in complex (i.e. non-flat) components with a focus on oven vacuum bag prepreg moulding [25,26], and the recent review on Automatic Fibre Placement (AFP) by Brasington et al. [27], each of which identifies different defects and organizes their information differently. Within the current activity, the focus is on autoclave and oven vacuum bag manufacturing of monolithic prepreg using hand layup and based on the above given definition uses the following list of defects:

1. Changes in cured ply thickness
2. Voids
3. Wrinkles (i.e. out-of-plane change in fibre direction)
4. Waviness (i.e. in-plane change in fibre direction)

This is only a small selection of what is contained in the taxonomy of Potter [1] which covered every deviation possible in the entire manufacturing processes, but it is believed to be the appropriate subset given the stated definitions and considerations.

The above listed defects are also selected with the construction of the digital twin in mind. The description of any defects must fit into the tools used to generate the meshes used for numerical analysis. Here defects are in general defined relative to the pristine mesh as distortions of said mesh. As such, it is possible to create a hierarchy of features, so as to define the mapping from the pristine to the true mesh in the lowest number of steps. Consider the corner specimen shown in Fig. 1, which is rich in defects. From visual inspection, the increased thickness of several plies and the presence of voids is apparent, while any in-plane waviness is difficult to determine from this image due to the viewing angle. The challenging question for characterisation however is whether there is wrinkling or not. While individual plies do deviate from their path in the out-of-plane direction, each ply more or less appears to follow its neighbours' edge, allowing for inter-ply voids. It can be argued that this cross-section is entirely characterised by the addition of only two sets of features: (a) ply thickening and (b) voids. Any out-of-plane shifts in ply positions/fibre paths, can be directly linked to ply-thickening and/or voids occurring between the ply in question and the adjacent surfaces. In other words, the plies are nominally running along the "base surface" provided to them by the material below them. Introduction of increased ply-thickness and voids into a model would implicitly require the shifting of the layers "above", hence removing the need to separately define the layer as wrinkled. This example highlights the need to address and characterise feature descriptions holistically, as they often occur together and their characteristics (e.g. size, location, severity) are linked.

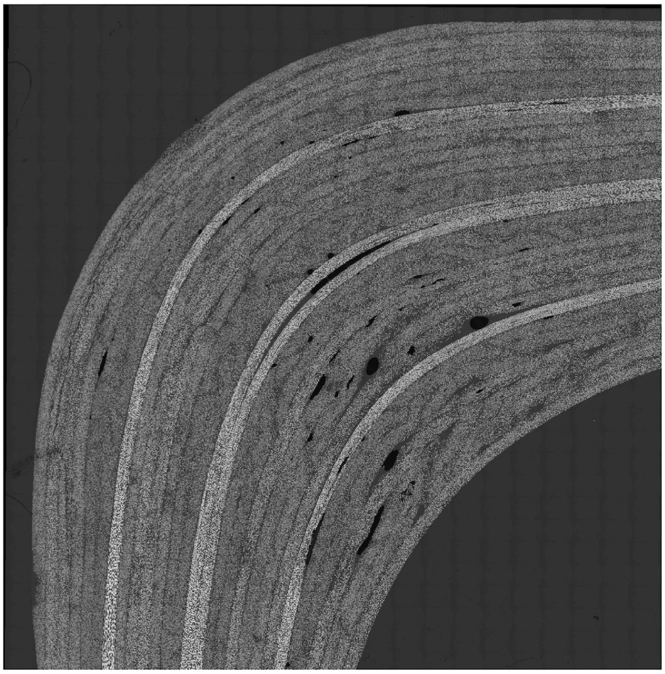

Fig. 1. Micrograph image of defect rich corner.

Given the desire within digital certification to link geometry and process to part quality in the form of the occurrence of defects and the demonstrated need to handle feature descriptions holistically, a new taxonomy format is proposed that, for a given process, centres on geometric features and linking the defects that are commonly found in such geometric features to the influential parameters that can affect the occurrence of those defects in that geometrical feature. The logic is visualised in Fig. 2 and the current developed taxonomy for this paper can be found in the Appendix.

To populate the taxonomy, the literature is consulted for each of the identified defects (cured ply thickness, voids, wrinkles, and waviness) to understand the current practices regarding characterisation, the observed trends and influencing parameters. The reliance solely on data covered in the available literature for the chosen process of monolithic hand-lay up prepreg, results in an incomplete coverage. The taxonomies provided are hence intended only as a starting point and means of capturing the new framework within which to assess features and defects for the virtual certification future. In the following sections the collected data is discussed and for each defect the need for improvements in the approach to characterisation to improve understanding is also discussed.

3. Change in cured ply thickness

3.1. Current practices

Cured Ply Thickness (CPT) is a common measured quantity and as covered below there is a fair amount of research looking into its variation. This is in part because standard measurement tools like Vernier

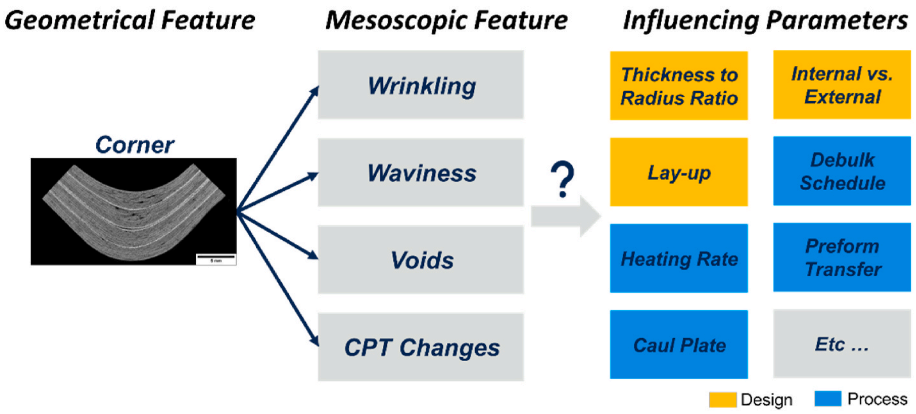

Fig. 2. Example logic behind proposed taxonomy.

Callipers, as well as digital rulers on micrograph images, can easily be used to take these measurements, though modern studies do also deploy lasers to scan parts and determine thicknesses [28]. However, CPT is generally not measured ply-to-ply, but rather represented by either the total laminate thickness or computed by dividing the cured laminate thickness by the number of plies. Returning to the example case in Fig. 1, it is clear that this effective averaging of the changes in ply thicknesses is not representative and does not allow for true recreation of the internal features. In this instance the changes in CPT only occur for tighter radii plies and only for those orientation where fibres are not along the corner direction. This means that fewer plies are seeing a larger change in their CPT then the average would suggest and also will change the local stress states that will occur.

3.2. Current trends/correlations

A summary of key literature for the purpose of identifying relevant parameters effecting CPT, are provided in Table 1 and summarized here. Most studies into variation in cure thickness are focused on corner specimens with autoclave curing, and have showed how cured thickness of corner pieces are influenced by both lay-up and type of corner (i.e. external vs internal) [29], based on total laminate thickness measurements both before and after cure. Generally thinning is observed for external corners and thickening for internal corners. For very small radii, however, it has been found that both internal and external corners show some level of thickening at the apex of the corner [30]. It has further also been demonstrated that the type of caul sheet material significantly effects the corner thinning for external corners going from almost no thinning up to around 10% of the flat laminate thickness depending on caul sheet material [31], with some work also showing the influence of using partial caul sheets in corner pieces to prevent local thickening and thinning [32]. Finally it has also been reported that for internal corners the change in cured laminate thickness is linked to the ratio between the radius and the laminate thickness [33].

For oven curing, it has additionally been shown on corners, that cured laminate thickness has a significant sensitivity to any deficiency in the vacuum pressure [34]. Improvement in consolidation of internal corners has also been found for oven curing when debulks at elevated temperatures were used [35]. A multiparameter study combining laminate thickness, material type, corner type, with corner angle has shown the combined effect of those parameters [36] and separately the influence of lay-up has also been observed for oven cure of corner parts [28].

Table 1
Overview of literature into change in cured ply thickness.

Source	Metric	Influencing Parameter	Geometry
[29,30]	Cured laminate thickness	• Lay-up • External vs. Internal	Corner
[31]	Cured laminate thickness	• Caul sheet material	Corner
[33]	Cured laminate thickness	• Radius-to-Thickness ratio	Corner
[34]	Cured laminate thickness	• Vacuum pressure	Corner
[35]	Cured laminate thickness	• Debulk temperature	Corner
[36]	Thickness variation	• Corner Angle • Thickness • Internal vs. External • Resin • Fabric Type	Corner
[57]	Cured laminate thickness	• Lay-up	Corner
[32]	Cured laminate thickness	• Local caul plate	Corner
[28]	Cured laminate thickness	• Lay-up	Corner

3.3. Proposed characterisations

In order to achieve realistic recreation of parts, the required characterisation needs to go from measuring the change in total laminate thickness, as observed in the literature thus far, to the change in thickness of individual plies or blocks of plies. This is needed for the purpose of virtual testing and certification for two reasons. The first is that this would allow capturing the reality and the underlying correlation between changes in ply thickness and layer orientation, currently captured indirectly by correlation between the full stacking sequence and changes in total laminate thickness and other influences on changes in CPT more accurately. The second reason is that, while not yet studied, it is likely that homogenising the change in CPT will result in discrepancies between the actual part and the virtual twin. If it can be demonstrated that strength predictions are not meaningfully influenced by the lack of attributing changes in thickness to individual plies, the current approach could be carried forward.

Turning to the parameters, it can be noted that the literature has been very heavily centred around the study of CPT within single curvature corners. A broader set of samples, even if they show little to no change in CPT, is needed to flesh out the correlations between the rich types of features that can exist and the changes in CPT relative to the baseline flat coupons. Furthermore, while an analytical model for predicting cured laminate thickness for corner pieces made using oven curing based solely on the radius to flange length and thickness to radius ratios has been shown to produce a decent overall fit [37], direct comparisons of the database used for the fitting and the predicted thickness does reveal a significant variation, indicating additional metrics are needed for a more consistent correlation. Fundamentally it is known that any parameter that effects consolidation will play into the CPT change. Some of the parameters not currently documented in the literature include:

- Resin viscosity profile
- Inter-ply friction

Table 2
Overview of literature into change into voids.

Source	Metric	Influencing Parameter	Geometry
[44]	Average Void Content Average Void Diameter	• Vacuum pressure • Autoclave pressure	Coupon
[48,102]	Average Void Content	• Autoclave pressure	Coupon
[29]	4 levels	• Viscosity profile of material • Bleed condition	Corner
[50]	Average Void Content	• Cure pressure • Dwell time	Coupon
[49]	Average Void Content	• Moisture content	Coupon
[46]	Average Void Content	• Pressure • Fibre content	Coupon
[51]	Average Void Content Void area distribution	• Heat rate	Coupon
[55]	Average Void Content	• Out-life	Coupon
[52]	Average Void Content	• Temperature Profile • Lay-up	Coupon
[34]	Average Void Content	• Vacuum Pressure	Coupon
[54]	Average Void Content	• Pressure during cooldown	Coupon
[58]	Void Content per ply	• Inter-ply friction • Fibre Young's Modulus • Part Radius • Part Thickness	Corner
[56]	Average Void Content	• Bagging consumables	Corner
[53]	Average Void Content	• Duration, temperature and pressure of intermediate dwell in two step cure	Coupon
[57]	Average Void Content	• Humidity	Corner
[28]	Average Void Content	• Lay-up	Corner

- Tool-ply interaction
- Fibre bed stiffness
- Cure cycle; ramp rates, dwell temperature, dwell times, pressure profile

Further studies are therefore needed to cover the above parameters and their influence on CPT, measured per ply or block of plies, for a wider range of components including those with repeated corners (e.g. C-section, T-stiffeners) and multiple curvature parts.

4. Voids

4.1. Current practices

For a recent and thorough overview of voids in composite materials, the review by Medhikhani et al. covers the formation, characterisation, and effects across multiple manufacturing process [17]. It can however be generally summarized that there is an almost exclusive use of average void content as the measure of voids from the earliest studies [38] to even the most recent works.

While voids, and especially average void content, can be detected with a variety of tools, use of CT imaging offers a non-destructive and high resolution method that allows extraction of the dimensions and positions of individual voids within the full 3D material volume [39]. Even for larger and more complex structures CT scanning can be achieved [40]. Mehdikhani et al. showed how such a characterization technique could allow for more refined descriptions of voids [41], including distributions of orientation, location of centroid, and major and minor axis [42] and have released their dataset for other researchers to study [43].

4.2. Current trends/correlations

The summary of currently studied parameters on the occurrence of voids within autoclave and oven cure manufacturing using hand lay-up for monolithic composite structures is given here and in Table 2. Early it was demonstrated how the vacuum and autoclave pressure influenced average void content [44] even in flat coupons. Since then it has been understood that in principle void growth is driven in autoclave and oven cure of prepreg materials by three main governing factors, namely: pressure, temperature, and moisture [45]. Void growth and movement largely occurs within the resin but the fibre bed is also of importance as it can offer resistance to the compaction pressure and hence reduce the hydrostatic pressure experienced by the resin [38]. As such fibre areal weight, fabric architecture, initial resin content [46] or, inversely, fibre volume fraction [47] can also potentially play a role. It is worth noting that while many studies will cover extreme ranges of pressures, the relationship between pressure and voids is highly non-linear [48] and with void content only rising sharply at very low autoclave pressures. Grunenfelder and Nutt, who investigated the influence of moisture content in the prepreg, found that autoclave cured parts had consistently close to zero voids while oven curing showed a significant influence on voids as moisture content increases [49]. Out-of-Autoclave curing, which can only rely on vacuum bag pressure, is much more sensitive to deficient pressure [34]. There is potentially also an interaction between the pressure and viscosity profile, as high pressure and low viscosity are needed together to suppress voids. To this end, studies have showed there was an "optimal" dwell time to reducing void content [50], as well as some influence from the temperature ramp rate on the size of the voids [51]. The combined effect of several different types of cure cycles with various lay-ups to on void content has also been investigated [52] alongside a multi parameter cross study for two material systems to evaluate the influence of the temperature, pressure and duration of an intermediate dwell in a two-step cure cycle [53]. Interesting results have also been presented showing the influence of consolidation pressure during cooldown on voids, with reduced pressure resulting in increased voids concentrated in the outer layers [54]. Finally out-time of the prepreg, which results in slow curing of the part was also shown to play a role, with average void content increasing for laminates made with prepreg that has over 20 days of room temperature [55].

All of the above, however, was studied on coupons, and have no correlation or association with any features. The limited studies that have investigated voids within features have found that for corner pieces voids are elevated in corners and are influenced by the bleed condition and the material viscosity profile [29], as well as the bagging procedure and consumables [56] and the moisture content [57]. Numerically it has been shown that localised void content in oven cured internal corners is dependent on inter-ply friction, the fibre Young's modulus, and the part radius and thickness [58].

4.3. *Proposed characterisations*

From the beginning of void characterisation efforts and the exploration into their link to performance of composites parts, it has been highlighted that size and distribution need to be captured [48]. Wisnom et al. demonstrated, for singular voids introduced using tube and strip inserts, the influence of individual void sizes, with length showing the strongest correlation [59]. In their review, Mehdikhani et al. also stressed that shape, size, and distribution were needed to provide a more complete and consistent characterization when attempting to predict influence on performance [17]. While tracking all this information for every possible void might seem excessive, it is worth noting that unlike many of the coupon samples produced under extreme conditions which are studied in the literature, most manufactured parts have overall low void content and hence more fully characterising the reduced number of voids that do occur is not as infeasible. As with the CPT, further evaluation of the sensitivities of part performance to various parameters describing voids may further allow reductions in the data to be tracked. Especially in instances where voids are occurring together with other defects, the measures may only be needed for a select subset of the total number of voids. This is an area that needs significant further study to strike the appropriate balance between accuracy and data management.

The study of voids also suffers a similar lack of geometrical feature richness within the literature, though a wider set of parameters have been identified. The occurrence of voids in more complex components needs to be studied further and the interaction between process parameters previously identified and the parameters describing these geometric features (e.g corner type, radius to thickness ratio) needs to be established.

5. Fibre waviness and wrinkling

5.1. *Current practices*

Wrinkles, and to a lesser degree in-plane waviness, have been studied extensively in the literature as they are considered some of the most detrimental to performance. Three recent reviews were published on this that cover extensively the formation and effect of mechanical properties of wrinkles [60], the formation and classification of wrinkles [61], and the effect on mechanical performance of wrinkles for the purpose of identification of the significant parameters [18]. There is also the much older review by Kugler and Moon [62], which covers much of the earlier studies. Each of the above are excellent sources for a more complete overview of wrinkling across a wider class of materials and manufacturing processes than is considered here.

In general, to assess fibre misalignment early studies into the inherent variability of fibre alignment used destructive polishing and micrograph image techniques to sample the local fibre angle distributions [63]. Similar distributions were also complimented by wrinkle density plots (i.e. wrinkles per square centimetre), and averages of the off-axis angle, wavelength and amplitude of the wrinkles [64]. While the processing of images evolved in complexity [65,66], the principle of polishing the material to take micrographs and extracting fibre misalignment angles stayed common practice.

Other techniques, like ultrasonic scanning [67,68], thermo-elastic stress analysis [69], Eddy Current [70,71], and X-ray Computed Tomography (CT) [72] are also possible. X-ray CT is especially powerful as it can be used for many material systems and allows for directly visualising the fibres. The proliferation of CT imaging has also enabled direct NDT to simulation coupling with CT images being directly converted to meshes [73]. While powerful this obviously does not allow the kind of statistical analysis needed for digital certification as every CT scan is unique and cannot readily and meaningfully be compared to different scans of different parts made using different machines. Some level of abstraction, mapping, and extraction of metrics is needed to allow different cases to be coupled.

Table 3
Overview of literature into fibre waviness and wrinkling.

Source	Metric	Influencing Parameter	Geometry
[74]	Wrinkle Density Average angle Average Amplitude Average wavelength	• Laminate length	Coupon
[29]	3 types	• External vs. Internal Corner • Viscosity profile of material • Bleed condition • Lay-up	Corner
[77]	Wavelength	• Ply Bending Stiffness • Part Thickness	Corner
[75]	Wrinkle height	• Lay-up	C-section
[14]	None	• Part Thicknesses	Ramps
[28]	Aspect Ratio	• Lay-up	C-section
[76]	Arclength of wrinkle	• Part Shape • Lay-up • Thickness • Weave orientation • Flange length • Caul plate	C-Section and Omega Sections

The most commonly used definitions of fibre waviness or wrinkling is based on the maximum deviation angle, the wavelength, the amplitude, and the severity/aspect ratio (i.e amplitude divided by wavelength), e.g. Ref. [20]. This single or limited parameter characterisation is achieved/facilitated by an assumption in the overall shape of the fibre misalignment. When mapping and simulating wrinkles and waviness, sinusoidal shape functions are often used. While offering a decent starting point, it is readily apparent that this does not fully capture the broad spectrum of possible wrinkles and waviness that is possible.

5.2. *Current trends/correlations*

The study of waviness and wrinkling and their influencing paraments, as can be seen in Table 3, is actually fairly limited as many studies artificially induce fibre misalignment to study their effect rather than study the natural occurrence of these defects in complex parts. Much is theoretically known and generally accepted about the phenomena inducing and influencing wrinkling and waviness, but little has been experimental demonstrated and documented in the available literature. For example, the tool-part interaction is a well-established cause for wrinkling but was demonstrated only once by Kugler et al., who investigated the influence of coupon length on the occurrence of ply wrinkling and waviness [74]. The length of the coupon was rationalised as driving the tool-part interaction.

The other well-established cause of wrinkling is curvature, where several authors have contributed experimental data, though there is overlap in parts and parameters studied. The type of corner (external vs. internal), the viscosity behaviour of the material, the bleed condition, and the lay-up have all been shown to influence wrinkling in corners [29]. For forming of thermoplastic stacks over a C-section containing a recess, a relationship was shown between the lay-up and the observed wrinkle defects, characterised using maximum height of the wrinkle [75]. The influence of lay-up and corner radius on wrinkling within the corners of C-sections has also been shown [28], with wrinkles characterised using their aspect ratio. For large thickness change components the thickness of the thin region of the laminate was observed to significantly influences the wrinkling at the end of the ramp down region [14], though no measurements were made. The most complete study looked at both C-sections and Omega shaped parts, using different lay-ups, total thicknesses, flange lengths, and alternating the orientation of the weave and the use of a caul plate [76]. The observed wrinkles and in-plane waviness were characterized using their size (i.e. arclength of the wave) to compare to the theoretically predicted excess length.

Finally, models have been used to show that in a corner piece, the ply bending stiffness and part thickness influence the wrinkle wavelength and there is a critical minimum length, dependent on radius, of the flanges adjacent a corner that are needed to induce wrinkling [77]. It was later also identified that there was a critical compaction pressure needed for external corner specimens to develop wrinkling [78]. As far as the authors know, these trends have not been experimentally validated or explored.

5.3. *Proposed characterisations*

Waviness and wrinkling, much like voids, has historically been insufficiently characterized and it has long been noted that the majority of wrinkles and waviness studied in the literature are not representative of real parts [79]. While the numerical study by Xie et al. showed that the exact shape function does have an influence on the predicted strength, even though all functions tried were of the sinusoidal family, it was also shown the relationship between strength and traditional metrics like maximum angle and aspect ratio are not monotonic [80]. From the limited and inconsistent characterisation currently in use, a drastic change is needed.

A recent numerical study showed the significance of the assymetry of wrinkling in terms of laminate tensile and compressive strength for both cross-ply and quasi-isotropic laminates [81]. It has also been shown numerically that for embedded wrinkles, the relative size and aspect ratio of the area containing the wrinkle and its positioning influence the strength and stiffness of the composite laminate containing the wrinkle [82,83]. For surface wrinkles in wind-turbine blades it was shown that depth and wash-out degree (i.e. rate at which the wrinkle dissipates through the thickness) significantly influenced the relationship between maximum angle of the wrinkle and predicted strength [84]. And the specimens by Weber et al. [76] demonstrate that wrinkling and in-plane waviness are closely coupled and often co-occur to compensate for excess length. Hence, their individual and combined description and relative severity and positioning are also of interest. Netzel et al. similarly observed combined wrinkling and voids [28], and as both act as local stress concentrators their relative positions also must be captured. Wrinkles and waviness would also further require qualitative characterisation following Thor et al. [61] to logically categorize them into similar morphologies. From the above, a tentative list of characteristics is proposed:

- Maximum angle
- Aspect ratio
- Wash-out degree
- Relative through-thickness position
- Wrinkle type (e.g. surface, embedded, folded)
- Proximity to other defects

Further manufacturing trials, expanding the geometrical and process parameters investigated, are needed to both fill out the database as well as to identify further variations to evaluate. The above list of characteristics is bound to evolve as further studies are carried out. To this end XCT scanning is again a powerful tool as the raw files can be kept and reprocessed to extract novel parameters as and when they are identified.

6. Measuring for digital twins

The required improvements in defect characterisation and data collection identified in the previous sections are reliant on effective and detailed inspection techniques. It is already common practice to inspect the final component, but for the purposes of feeding a manufacturing process digital twin, more detailed data capture is needed than currently provided. Measurements made during production can track the development of the part quality through the various stages to improve data collection. In this section, current off-line and in-process measurement techniques as well as open research opportunities within inspection for digital twins are briefly discussed.

6.1. *Off-line measurements*

The current approach to part characterisation resides mainly in the form of off-line measurements, which happen after the manufacturing process is complete. These processes usually involve dimensional metrology and a mixture of non-destructive testing (NDT). Novel developments are constantly extending the abilities of various NDT including ultrasound [85], thermography [86], X-ray CT [87], Eddy Current [88], and Microwave [89] inspection. Traditionally, these tools are deployed to check dimensional tolerances, average void content [17], and inspect for larger inclusions, all of which are in turn used in the concession process to determine is a part is fit for service, needs repairing, or has to be scrapped. Some of the more mature techniques are also deployed in structural health monitoring [90].

While the introduction of higher resolution NDT techniques, specifically X-ray CT, can allow for very complete reconstructions of the internal features, the processes are time consuming, part size limited, and involve prohibitively large data sets. Use of trained AI/ML to process raw images [91] or other algorithmic image processing solutions [92] can allow data processing to be carried out in a more automatic, reliable, and time efficient manner, but the required infrastructure both for conducting the scans and processing all the data remains a significant bottleneck that would result in parts being parked while they await scanning and processing. To avoid this, in-process inspection, where information on part quality is gathered and the internal features are identified and characterised as value is being added to the part, offers a valuable alternative.

6.2. *In-process measurements*

With in-process monitoring, data collected during or between different stages of the manufacturing process (e.g. ply deposition or forming, de-bulking, curing) can be leveraged in two ways. Firstly, it can reduce and hopefully remove the need for more costly and time-consuming inspection of the as-manufactured part. Secondly, the data can be used to make in-process corrections, to reduce concession rates and hence improve the overall efficiency and quality of production.

As in-process inspection can have access to individual layers as they are deposited/formed, surface/near surface techniques such as 2D/3D cameras [93], metrology, and non-contact NDT can be used to inspect incoming material, detect defect precursors, and automatically inspect tools/equipment [94]. Combined with careful tracking of various process parameters (e.g. pressure, temperature, time, relative humidity), a comprehensive image of the manufacturing process can be established. Utilising either process simulations (e.g. for void development [95]) and/or historical data, the final part quality could then be predicted.

While the potential upsides of in-process inspection are significant, which underpins the recent rise in popularity as a research topic across multiple industries [96] and manufacturing processes [97], there are also still several hurdles to be overcome. One major complication that needs to be addressed is that for industrial scale parts, any inspection technique deployed in-process must be reliably deployable at scale and, as already stated, ideally be non-contact to prevent interference with the part in its uncured state. Some techniques, such as those used to assist in and check ply location using laser projections and image analysis, have already started to find their way into industrial use (e.g. Aligned Vision). While such techniques are valuable in ensuring geometrical tolerances are met, they do not yet relay the type of data and resolution needed to fully inform a manufacturing digital twin. While image analysis techniques, assuming controlled camera positioning and lightning, can be used to detect surface and edge defects, they cannot provide information on anything that is buried and so have limited use past the initial deposition stage. To track the part and any sub-surface features which may develop in the debulk stages, more advanced imaging techniques are needed.

Another difficulty in achieving in-situ inspection is sensor integration. Ideally inspections should add no additional time to the part manufacturing process, therefore stand-alone sensor set-ups that require significant set-up time are to be avoided. One avenue to achieve this is through smart tooling, where sensors can be embedded directly into the tool ready for active measurements during the entire process or intermittent measuring at pre-determined intervals. For example, the void sensing technique based on measuring electric potential across thickness of a part proposed by Gueroult et al. [98] for Resin Transfer Moulding, could be integrated directly into two sided tooling, or in the case of single sided tooling could be deployed in the base tool with the scan carried out using a movable top electrode. One of the limitations of this specific technique is the reliance on non-conductive fibres, making it unsuitable for use with carbon fibre materials. This highlights a second key challenge with regards to in-situ inspection, namely that different techniques are often applicable only to specific material systems and/or production processes. Another great example of this limitation in an otherwise promising technique is Eddy Current Testing (ECT), which has shown significant promise in terms of delivering in-line inspection of fibre orientation, waviness, and wrinkling [99]. The issue here is that ECT relies on the conductivity of the fibre, and so is not applicable to glass fibres. Furthermore ECT requires different set-ups to best detect different types of fibre path deviation (i.e. in-plane waviness [100] vs. out-of-plane wrinkling [71]). The latter is in some ways a strength of ECT as the same basic system components can be deployed to detect and distinguish between different defects, even including debonds, delaminations, and cracks [88].

This makes ECT somewhat unique as many other available scanning techniques often produce only a single signal that does not necessarily allow complex defect states to be decoupled clearly. For example, ultrasound technique signals generally require significant calibrating efforts whenever applies to a new material. While the most commonly used to determine overall voidage [17] and having been demonstrated as having some capability for detecting out-of-plane wrinkling by Larrañaga-Valsero et al. [85], the reliable extraction of these defects and the separation of complex defects states is still an ongoing issue. This is further complicated by the fairly high sensitivity to the sensors motion relative to the scanning surface, which is an issue also shared by ECT, and the potential need for coupling agents, which will generally not be appropriate to use on un-cured materials, whether dry fibres or un-cured prepreg. Similar issues are suffered by thermal inspection techniques, which have been deployed successfully as an in-situ inspection technique to track infusion [101]. Again, however, insufficient separation of signals has been achieved to reliable use such technologies to detect and characterise complex defects and the method itself may be inappropriate or inapplicable to uncured parts.

As things stand, the one process in which extensive in-situ inspection has significant promise and has already seen some use is in automated processes like AFP and ATL, as also noted by Brasington et al. [27]. Due to the use of robots for material placement, sensors can be integrated directly into the robot and the lay-up head to get in-line measurements of the in-coming material, the critical process paraments (e.g. temperature and pressure) as the initial deposition takes place, and inspection of the material post deposition. In automated deposition the information gathered from such sensors could further be used to automate certain corrective actions, including filling of any missing tows/tapes.

6.3. *Research opportunities*

The big question in integration of digital twin technologies in the manufacturing process of composite structures relates to how to collect the required measurements without slowing down the manufacturing process. Given the commercial interests, no reduction in production rate is acceptable as this directly reduces the financial viability of implementing these technologies. In order to address the need for rapid and rich data collection the following research questions remain open:

1. What features must be detectable and which of their characteristics must be measurable?
2. What inspection techniques or combination inspection techniques have the potential to deliver these datasets across different materials and for different moulding approaches?
3. What sensor and data processing developments are needed to achieve robust measurement systems that can be deployed in industrial settings and with minimal human intervention?
4. What logistical investments are needed to facilitate data management and storage required to operate such intense data collection efforts?
5. How can the digital twinning approach be standardised considering the wide variation in factory lay-outs, machines (e.g. level of digitalisation, maintenance, space), human error and industrial best-practices?

7. Conclusions

The introduction of AI/ML, digital twin, and Bayesian tools into the design, manufacturing, and certification of composite structures is a promising field. Within the context of this paper the application of interest is that of a manufacturing process digital twin which can be used to ensure part quality in serial production. To achieve its full potential, significant data sets are needed to build the understanding, train the algorithms, and develop baseline probabilities. This data must also be fit for the purpose of sufficiently describing the mesoscopic features, known also as defects, to allow these to be recreated in the digital space with sufficient fidelity to allow predictions of strength distributions to be reliable.

Four key defect types that are common in autoclave and oven curing of prepreg composite materials (i.e. changes in cured ply thickness, voids, fibre waviness and wrinkling), were identified as relevant after consideration of what can and should be considered a true defect. From the surveyed literature, it is determined that the required level of fidelity has not historically been achieved, with most features being heavy homogenised and/or simplified in the characterisation process. Further, while a lot is generally accepted as influencing the occurrence of defects, coverage of different parameters and geometrical features is severely limited with most studies only considering either coupon or corner geometries. Hence it was stressed multiple times that additional manufacturing trials and studies are needed to fill the gap and generate new data with enhanced characterisation. It is further stressed that the study of cases in which multiple defects co-occur, including at various levels of severity, is completely missing and must be addressed to ensure proper characterisation of realistic defects. The inclusion of parameters describing proximity to other defects are key to ensure a sufficient fidelity of the data to allow assessment of the impact of different defect states to the performance of the part.

A new taxonomy structure was also proposed to capture the dependencies of defects from the viewpoint of digital certification. In this new taxonomy the focus is on identifying the relevant variations occurring in serialised production of composite components for any defect known to occur due to certain geometrical features. While the provided taxonomy is a work in progress, it offers a new starting point for thinking about and discussing defects. The structure of the taxonomy is such that different geometrical features (e.g. ramps, joggles, double curvatures) as well as different manufacturing processes, which might see different types of defects and/or influencing parameters, can be developed easily in parallel. For example, the application of this taxonomy to AFP could start with the work of Brasington et al. [27] who have identified a comprehensive list of defects. As far as existing literature couples these defects to certain geometric features and influencing parameters, the taxonomy can be built. Where no known associations exists, this can be used to identify those cases that require further study. This is ultimately the true power and use of the taxonomy, not only organise the existing knowledge but to clarify that areas of knowledge and data sets that are incomplete or missing.

From the work reviewed here and taxonomy built for the hand lay-up processes on a corner geometry, it is clear that much work is still needed. Additional studies will initially be required to serve two purposes. Firstly, further investigation will have to identify the level of characterisation that is actually needed as this is far from a settled question. In parallel these studies will be filling out the taxonomy structure and providing the data sets needed to bring the available data to the newly identified level of fidelity and ultimately obtain the required volume of data required for the ML/AI techniques to be deployed effectively. In situ inspection is a key technology in achieving this as it enables gathering of large quantities of data without adding additional bottlenecks in the production line. The two key limitation that need to be addressed still for effective in-situ inspection are identified as the lack of resolution and confidence in NDT techniques that can be deployed within the manufacturing process and then establish the clear link between observations made during the process and the final part quality obtained at the end of the process. This means that in the short term and likely during initial design and certification of new parts, both in-situ measurements and final part inspections will be needed to baseline the process to allow quality of parts in serial production to be determined exclusively from the in-situ measurements.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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9. Appendix A. Novel Taxonomy

The purpose of the new taxonomy approach is to frame the identification of defects and their influential parameters within the certification mindset. Within the standard testing pyramid, the coupon test are connected to the final part through a hierarchy of structural details and components. It is these structural details, referred to here also as geometrical features, where the introduction of defects occurs and hence the taxonomy uses these elements as the core grouping blocks. For each structural detail a tree can be created with under it the defects and under these the parameters affecting those defects as they occur in that feature.

From the current literature only one tree can be reasonably completed, which is centred around the corner. A start can also be made for “Repeated corners (e.g. C-sections) and “Thickness Transitions” (i.e. ramps), and possible defects and parameters not yet investigated can of course be highlighted. These two trees are shown in Figure A 1, Figure A 2, and Figure A 3. These figures clearly highlight that while a significant number of parameters have been identified or can be extrapolated between cases (e.g. what effects a single corner is likely to influence repeated corners) the coverage of actually data is sparse.

Fig. A 1. Taxonomy for "Single Corners".

Fig. A 2. Taxonomy for "Repeated Corners".

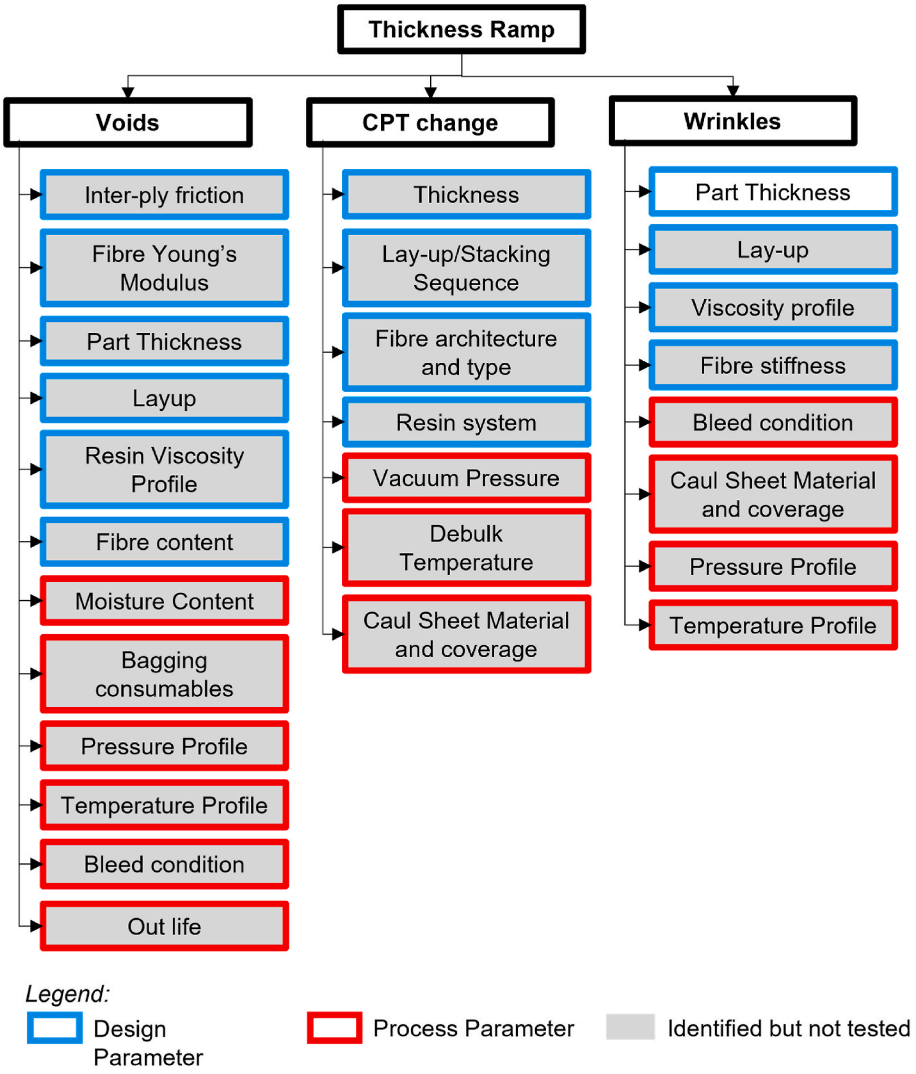

Fig. A 3. Taxonomy for "Thickness Changes".

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