RAPID TOOLS FOR AN AFP MANUFACTURING DEFECTS ASSESSMENT FRAMEWORK

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ABSTRACT

This work formulates an automated fiber placement (AFP) defects assessment framework. Such framework assumes AFP manufacturing processes are able to identify manufacturing defects via automated inspection systems and intends to provide rapid analysis tools to create a defect assessment loop. The defect assessment loop defines an automated analysis process during AFP manufacturing to minimize the number of manual repairs on the part, thus accelerating AFP manufacturing of composite structures. This defects assessment loop advantages automated inspection data to evaluate the influence of encountered AFP defects on a ply-by-ply basis. Structural evaluation is based on strength criteria using local-global finite element models. Local models affect the global part model via material property reductions. Schemes to reduce material properties using the local models are the main enablers of this framework's automated assessment capability. Finally, we discuss the main technical challenges to realize the feasibility of this framework.

1. INTRODUCTION

The ability to assess part structural integrity, in-situ, as manufacturing defects appear allows prompt evaluation of necessary repair, and thus will result in shorter lead times. Streamlining the automated fiber placement (AFP) manufacturing process with such an online defects assessment capability accelerates the development of advanced composites. This work formulates an AFP defects assessment framework. Such framework assumes that during AFP manufacturing processes manufacturing defects are identified via Automated Inspection Systems (AIS) and intends to provide rapid analysis tools to create a defect assessment loop. Rapid tools are needed to support the loop online and in-situ.

The use of analysis tools to assess AFP manufacturing defects has more than a decade of research. As early as 1993, research on using finite element (FE) models to account for AFP manufacturing defects has taken a global-local modeling approach. Cairns et al. [1] study stress concentrations using a hierarchical modeling scheme with a global model for the notched laminate, and a local model for the inhomogeneities at the notch tip. They use the term "inhomogeneity" and refer to it as a consequence of the AFP manufacturing technique. Five years later, Sawicki and Minguett [2], follow up the studies with experimental trials using IM6/3501-6 tow material. This study focused on the strength reduction of gaps and overlaps due to out-of-plane waves. When a gap or lap is created, the next ply laid on top shows a waviness on that empty region, which according to the authors is the main driver of the 5-27% strength reduction. Li et al. [3] concur with Sawicki and

Minguett [2] on the weakening mechanism that a gap will produce an out-of-plane waviness in the ply above it. Since AFP manufacturing is done on a ply-by-ply basis, a defect identification process necessitates a memory mechanism of past ply defects. Abdi et al. [4] also propose a hierarchical analysis. However, their analysis is of higher fidelity combining macro-mechanics and micro-mechanics instead of just a global-local approach. Abdi et al. [4] multiscale failure analysis techniques are also applied in Marrouze et al. [5] to discuss the effect of gaps on strength and stability of stiffened composite panels.

Blom et al. [6] focus their research on a particular type of gap described as a small triangular resin-rich area due to tow drops on the boundaries, and the impact of these on the strength of variable-stiffness laminates. Their model parameterizes the tow width and laminate thickness, amongst others. Of particular interest to this work, they find a direct correlation between the tow-width and the strength. Wider tows result in lower strength. These results are purely based on FE simulations. On the other hand, Croft et al. [7] experimentally investigate four different AFP defect types: (i) gap, (ii) overlap, (iii) half gap/overlap, and (iv) twisted tow. Their work found that the effect a defect has at the lamina level (around 5%) is smaller than the effect at the laminate level (up to 13%). This justifies the need for local FE models to capture the complete stacking sequence. Marouene et al. [8] show how the spatial location of the gaps and overlaps can create negative, negligible, or positive effects on the open-hole compression strength. Finally, Lan et al. [9] add empirical-based knowledge on the compression strength of laminates with embedded gaps and overlaps. An important result from their study is that if the autoclave process uses a caul plate, it can allow defects to "heal", indicating that the structural integrity assessment depends on the autoclave process parameters as well.

In summary, the literature holds several experimental investigations on the effect AFP manufacturing defects have on the mechanical properties. Typical defect types are gaps, overlaps, and wrinkles. Such experimental approaches are complemented with FE models for structural integrity evaluation. This paper describes a two-step AFP defects assessment framework that incorporates the FE-based knowledge of defects into an online assessment loop to reduce manual repair time. Section 2 describes the online defect assessment loop and identifies the needs of the analysis tools that support such automated assessment. To support online assessment of defects, knowledge of the local impact such defects have on the part is generated before manufacturing and captured in a knowledge base for online queries. Section 3 presents the offline database generation step. Finally, Section 4 summarizes the two-step framework and lists recommendations of future work needed to build an efficient framework.

2. ONLINE DEFECT ASSESSMENT

Krombholz et al. [10]**Error! Reference source not found.** already claim to an advanced AFP manufacturing system that increases the quality and productivity via an integrated sensor system. Their inspection system is claimed to be real-time by connecting the sensor processor to the numerical controller of the AFP machine. Technically, this framework's defect assessment loop is not real-time; rather it assesses the defects on a ply-by-ply basis after each ply is laid. However, this framework formulates the defect assessment as an in-situ analysis that loops over each layer's defects to assess intolerable defects that need repair. The defect assessment capability is said to be online because it is connected to the AFP manufacturing process as it is stacking consecutive plies on top of each other.

Figure 1**Error! Reference source not found.** illustrates the main steps of the online AFP defect assessment loop proposed in the current work. The loop starts after an Automated Inspection System (AIS) scans a recently laid ply of the part. The acquired data is entered into an AFP defects log recording the position and size of each identified defect. The defects are identified and logged based on a stipulated classification of AFP defect types. Such classification of AFP defects is user-specified. The AFP defects log represents the online interface between the AIS and the rapid analysis tools. The rapid analysis tools and AIS also share an offline interface that serves as the geometric correlation between CAD/CAM and FE models. However, once these models are correlated as a pre-manufacturing step the only communication interface with AIS is the AFP defects log. To ease exchangeability and human readability the log is written in ASCII format. Although read and write operations are significantly slower in ASCII format the integration efforts between AIS and the analysis tools reduces significantly if the AFP defects log is human readable. Once the defect assessment loop is verified a more efficient format for the AFP defects log can be implemented.

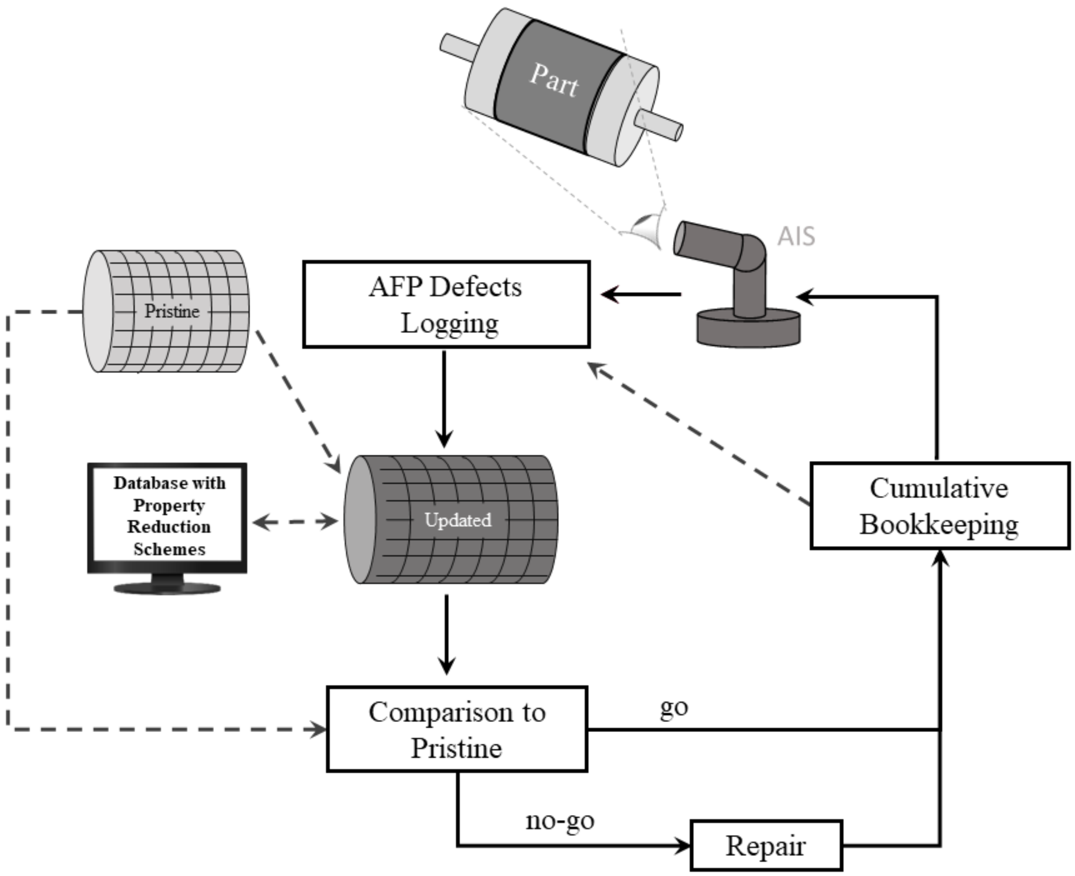

Figure 1: Schematic of the online AFP defect assessment loop

The AFP defect entries in the log file are mapped into an FE model of the discretized part geometry. If several defects map into the same finite element in the model, the decision automatically defaults to perform repair. For other pristine elements, a database composed of a collection of local FE defect simulation results and queried via Property Reduction Schemes (PRS) is used to rapidly reduce the element material properties. Section 3 explains in further detail the offline generation of this database and the associated PRS. The part FE model, with reduced properties, is then re-analyzed to predict the as-is manufactured structural integrity.

As a zeroth-order approximation, the structural integrity of the part will be evaluated based on the failure index at each finite element. The failure index is a metric that indicates local failure of the structure at a point. A failure index above 1 indicates the material failed at that point. Since the failure index is a continuous variable it also indicates how far the load-bearing material is to failure at each point. Note that in-autoclave curing is assumed to occur without introducing additional defects or mitigating the existing defects identified by AIS. Thus, the defect assessment is only due to the direct defects of the AFP manufacturing process.

Based on the up-to-date structural response a comparison against the pristine structural integrity is performed. This comparison bifurcates into a continue (go) or repair (no-go) command. Regardless of the command the cumulative bookkeeping step writes an entry on the AFP defects log of repaired or tolerated defects for the integrity assessment of future laid plies. Finally, control is passed back to the AIS.

Note in Figure 1 that the defects assessment is online-enabled due to the assumption that the pristine part and local defect stress concentration simulation results are readily available. The former is assumed available from stress analyses during design, while the latter needs to be generated offline before manufacturing. This database of local models represents a non-recurring cost of the defect assessment process and is described in the following section. Figure 1 denotes the use of these persisted data sources via dashed arrows.

3. OFFLINE DATABASE

3.1 Database definition

In an attempt to provide an analysis tool able to conduct a rapid assessment of a defect's influence on the mechanical properties of a manufactured part, there is a need to design an offline database. It will contain samples, in the form of digital coupons, of the potential configurations that can be encountered during the manufacturing process. The purpose of each sample is to provide a property reduction coefficient for a specific point in the design space. It will be necessary for the database to be constructed before the online analysis, therefore providing the possibility to interpolate the influence of a design variable on the part properties.

As a first step to create the database, the design variables of interest are selected and an appropriate range of variation for each of them are chosen to compromise between a sufficient coverage of configurations and an acceptable computation time. That process is directly related to the particular part under study and will therefore require a stress analysis of the pristine specimen as a reference to compare with coupons containing a defect. The database axes can be divided into two different categories. As shown in Table 1, the first group is composed of parameters used for the model definition and are specific to the specimen tested. That group includes the specimen shape and dimensions, the stacking sequence and the material chosen. To build the pristine model, which will be used as reference in the following steps, the necessary information is provided by the model definition parameters. The second group, on the other hand, is not specific to the specimen but to the defect type, its dimension, or its location through the thickness and in the plane. Each group serves a different purpose.

Table 1: Parameters for the database definition

Name	Range of variation	Type	Category
Shape		Discrete	Model definition
Specimen dimensions	Diameter, length, …	Continuous	Model definition
Stacking sequence	$\{[-45/90/45/0]_s, \ldots\}$	Discrete	Model definition
Material	AS4, IM7, …	Discrete	Model definition
Defect type	Gap, Overlap, Pucker, Twisted tow	Discrete	Parameter
Defect size	$[L_{min}, L_{max}]$	Continuous	Parameter
Load level	$[\sigma_{min}, \sigma_{max}]$	Continuous	Parameter
Ply orientation	{0°,90°,± 45°}	Discrete	Parameter

The objective is to observe the influence of manufacturing defects on the mechanical properties of a part, therefore the type of AFP-induced defects must be one of the database axes. Given the large variety of defects that can be encountered during AFP and in order to reduce the design space dimension, the list of defects of interest was down-sized to four of the more commonly faced defects: twisted tows, puckers, gaps and overlaps. Once the defect type is identified, the second concern for the model is to determine the orientation of the ply in which the defect is embedded, which can be determined from the stacking sequence at the defect location. Both of those parameters are discrete variables as opposed to the next two, which are the defect size $[L_{min}, L_{max}]$ and the load level $[\sigma_{min}, \sigma_{max}]$. L_{min} is the minimum size of the defect that can detected and L_{max} is denoted by the size of the finite element in the global model. With regard to the load levels, they are extracted from the previously mentioned stress analysis conducted on the pristine specimen. The last two previously mentioned parameters are continuous variables such that both a range of variation and step size are needed.

3.2 Database generation

Once all the parameters and their respective ranges of variation are identified, one digital coupon for each configuration is created. The digital coupons are based on the same model and their creation can therefore be automated through a programmed script. The dimension of the digital coupon is based on the size of a finite element of the pristine model. That choice facilitates the transfer of information between the two levels of modeling during the mapping process. The defect is then inserted into the center of the digital coupon. The defect's shape and size are mapped to the closest available discrete database parameters. The coupons are expected to provide the load distribution as well as a user-defined failure criteria value as an output. Those values are used to quantify the influence of each parameter on the elements of the whole structure and as local evaluations of the mechanical properties reduction for a finite amount of design points. These local evaluations allow interpolation of the influence of the parameters, for example through a response surface technique for continuous database axes and through linear interpolation for the discrete variables.

The steps followed during the generation process are presented in Figure 2. For each defect type and for each orientation encountered in the stacking sequence, a digital coupon is built. The digital coupon inherits several properties from the pristine model: the material properties, the stacking sequence, and the dimension of one of the global finite elements. The computation of the stresses and user-defined failure criteria are the basis for a property reduction scheme, explained in the following sub-section.

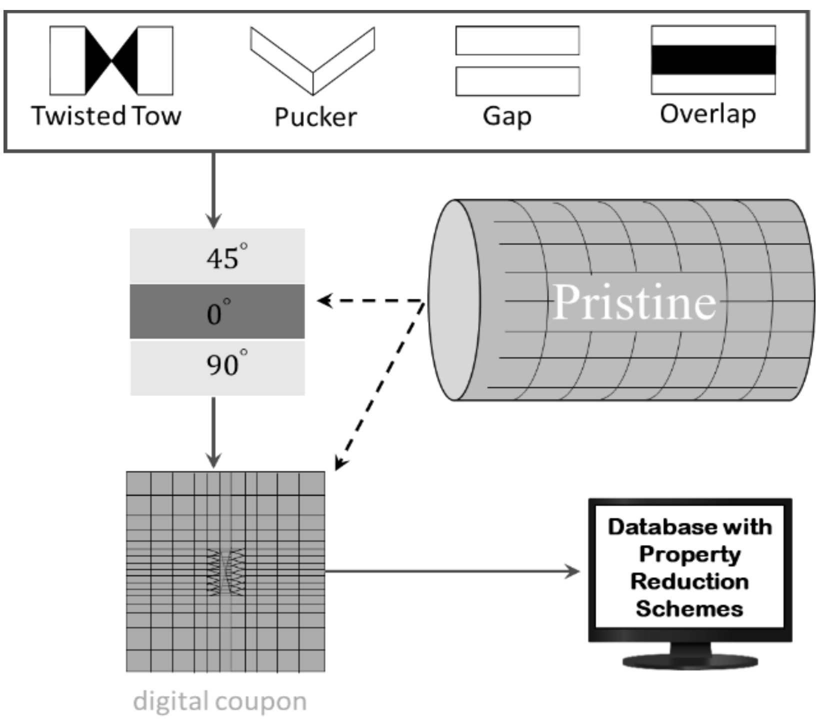

Figure 2: Schematic of the database generation process

3.3 Property Reduction Scheme

The aim of the Property Reduction Scheme is to provide a computationally evaluated knock-down factor on the material strength for a mesh element influenced by a given type of defect. The existence of such a pre-calculated database allows significant reduction in the duration of the online assessment process. Indeed, if one of the configurations tested during the building step is encountered during the manufacturing process, it is possible to directly access the knock-down factor previously evaluated. Otherwise, interpolation is employed to estimate the corrective coefficient to apply based to the pre-computed space design points.

The property reduction scheme provides the transition from the digital coupons to the global structure. The final aim is to be able to apply the knock-down factors generated from the database to the global elements of the part model. For this work, a cylindrical shell under compression is considered to assess the influence of the defects on the performance. Cylindrical shells under compression are known to be sensitive to *geometric* imperfections, while the defects under consideration here are more likely termed *material* imperfections. This framework allows the investigation of the sensitivity of cylindrical shells under compression with regard to the material imperfections and to determine if similar correlations with geometric imperfections exist.

4. CONCLUSIONS

Literature survey suggests influence of automated fiber placement induced defects on a part's mechanical properties such as strength or stability. That observation points out to the necessity of online assessment tools that rapidly evaluate the potential influence of a defect introduced during the manufacturing process. To address the need, the previous sections presented a two-phase plan. First, an offline database is built using a set of parameters as design variables to construct digital coupons. A representative sample of the design space is selected as base configurations to be considered during the computation process. These models are thereafter used to evaluate a knock-down factor to apply to material properties due to the influence of the defect. In a second step, the data obtained through the digital coupon computation is used to interpolate the knock-down coefficient values for the whole design space. Finally, the online assessment loop will take advantage of an automated inspection system to generate a log of encountered defects; which will thereafter be mapped within the finite element model by leveraging the information provided by the database regarding the material properties reduction. The stress analyses re-computation will then offer valuable information regarding the need to repair the detected defects.

To build an efficient defects assessment framework, there should be a trade-off between rapid performance analysis and model fidelity. However, the framework encounters several challenges to achieve the objective of providing a rapid analysis tool. It should be capable of capturing the minimum required fidelity to effectively assess the influence of the defects on the part's structural integrity while being relatively faster than its manual counterpart. To circumvent these challenges, the efficient framework can be enhanced by using suitable sampling strategies for modeling the digital coupons. In addition, a response surface approximation can be used to evaluate the knock-down factors for configurations that were not considered in the sampling process. For future work, the rapid analysis tool will be built and tested during an online manufacturing simulation to verify its efficiency. In addition, pristine and defective cylindrical shells will be manufactured and tested under axial compression. A comparison between the manufactured cylinders will assess the potential influence of a defect configuration that might be encountered.

5. ACKNOWLEDGMENTS

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