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IN-SITU STRUCTURAL EVALUATION DURING THE FIBRE DEPOSITION PROCESS OF COMPOSITE MANUFACTURING

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Abstract

Within the European funded project ECOMISE a new approach for composite manufacturing is developed. This approach provides key technologies for industry 4.0 in order to maximize process efficiency at reduced cost and time while maintaining structural requirements. In detail, process simulation methods, online process monitoring systems as well as methods for in-situ structural evaluation and process adjustment in case of process deviations are implemented and linked via databases. This paper describes the new overall concept as well as the specific in-situ structural evaluation approach, exemplarily applied to the fibre deposition process. Prior to manufacturing typical manufacturing features such as locally varying fibre orientation, gaps and overlaps are studied based on given knowledge from previous manufacturing as well as from process simulation. The effect of selected features on the structural properties is investigated for the expected parameter ranges. The real detected features are provided by an online monitoring system during the fibre deposition process. Based on these results an in-situ structural evaluation of detected features is performed already during manufacturing in combination with a decision making with respect to required part correction. The developed key technologies and tools for the in-situ evaluation process are presented, and their prototype application is shown during manufacturing of an aeronautic wing cover demonstrator.

Keywords: In-situ structural evaluation, effects-of-defects, multi-scale analysis, surrogate modelling, gap, overlap, automated fibre placement

Acronyms:

AFP	Automated Fibre Placement
DFEM	Detailed Finite Element Model
DOE	Design of Experiment
EoD	Effects of Defects
FE	Finite Element
GFEM	Global Finite Element Model
MoS	Margin of Safety
NDT	Non-Destructive Testing
RVE	Representative Volume Elements

Symbols:

A	Area (mm^2)
E	Young's modulus (N/mm^2)
G	Shear modulus (N/mm^2)
v	Poisson's Ratio (-)
S	In-plane shear strength (N/mm^2)
T	Thickness (mm)
X	Strength in fibre direction (N/mm^2)
Y	Strength transverse to fibre (N/mm^2)

Super- and Subscripts:

C, -	Compression
T, +	Tension
x, y, xy	in fibre direction, transverse to fibre direction, in-plane
eff	effective

1. INTRODUCTION

Contemporary composite part development and manufacturing, in particular of high performance light weight structures, is still requiring a high effort in order to find optimal process parameters and to meet required qualities and tolerances. In case of fibre deposition the processes of pick and place, tape placement or fibre placement are industrially applied enabling a high degree of automation, while meeting high structural requirements. However, depending on the complexity of the part as well as on the selected process technology and material type the resulting semi-finished products still contain different manufacturing deviations that are to be considered. Already in case of simple fibre deposition onto flat surfaces tolerances of fibre orientations, ply contours or ply thickness as well as gaps and overlaps appear (Lichtinger, et al., 2013). In case of more complex shaped geometries or fibre steering tapered gaps and overlaps cannot be avoided, and process difficulties lead to fibre waviness, wrinkles or twisted tows (Lukaszewicz, et al., 2012). In order to balance these tolerances and to avoid defects during fibre deposition optimum process parameters are usually determined for each specific application taking into account prior defined structural requirements. Depending on the complexity of the part this requires a high effort, but certain risks for manufacturing defects still remain. Furthermore, structural requirements are often derived from simplified and conservative rules, while neglecting possible reserves for individual applications. This conservatism comprises two drawbacks:

On the one hand structural reserves are often not exploited. On the other hand non-added value manufacturing and rework processes unnecessarily increase manufacturing costs.

In order to improve the process robustness isolated monitoring systems are already applied to monitor process parameters and to provide information for process adjustments. Yet, these adjustments are performed against prior defined conservative tolerances of respective process parameters. No information is provided on the actual material properties affected by process deviations. Moreover, no evaluation is performed whether a certain knock-down of material properties is significantly affecting the structural performance of a part, especially in case of a defect located in minor loaded areas of the part.

Aiming at significant reduction of manufacturing costs, rework and part rejections a new approach is presented within this paper. This approach provides an in-situ structural evaluation of part deviations occurring throughout composite manufacturing, exemplarily shown for the fibre deposition process. By integrating an in-situ evaluation an early feedback is given, allowing for decision making whether to allow or correct current defects before handing over to the next manufacturing step.

In order to enable this throughout approach following key technologies are to be provided. Online monitoring systems must be capable to measure relevant part and process parameters and also to characterize in real-time with respect to typical defects with required reliability. Further, profound physical understanding and efficient analysis tools are required for real-time evaluation of the actual effects of defects, i.e. to assess the influence of certain defects on the structural behaviour.

Within the following chapter 2 the overall evaluation process is explained by providing information on required methods and tools as well as related input and data mining. For this workflow special care was given to the integration of highly efficient methods with required accuracy in order to meet real-time evaluation capability. Subsequent chapter 3 is dedicated to the developed methods required for evaluation of defects on the local defect level. The focus is laid upon the analysis of fibre deviations during the automated fibre placement process (AFP). Chapter 4 describes the procedure for evaluating the resulting structural performance taking into account these local deviations. The procedure is demonstrated by means of an aeronautic wing cover manufactured by AFP. Chapter 5 concludes the results and gives an outlook for further research suggested.

2. EVALUATION PROCEDURE

Current process chains of composite part production already include several quality assurance checks. Incoming goods (e.g. fibre and resin material) are checked with respect to their specifications. During manufacturing sensors are increasingly applied to capture process parameters such as time-dependent pressure or temperature. Traveller coupons are additionally used for subsequent material analysis, and NDT techniques are applied directly after manufacturing in order to check e.g. for fibre waviness, pores, delamination or geometrical deviations. Baseline for all of these quality checks are prior defined global tolerances for a component of a certain material. Yet, no distinction is made between differentially loaded areas. Also quality checks during manufacturing are only referred to process parameters but not directly to determining structural properties. Moreover, current evaluation methods are involving significant manual effort and thus, hindering an automated and direct feedback and early decision making on acceptance, adjustments or rejection.

The novel evaluation procedure enables an early and fast evaluation of manufacturing deviations with respect to their effect on the structural behaviour on component level. Special care is taken to the analysis of the effects of process deviations on the resulting structural mechanical properties. The development and integration of highly efficient methods for so-called in-situ evaluation and assessment need to consider different types of deviations directly during manufacturing. Such deviations are classified in two categories:

- Defects, which can be directly considered within the global structural analysis (e.g. fibre angle deviations, thickness deviations)
- Defects, which have to be analysed using detailed local models in advance to the global structural analysis (e.g. gaps, overlaps, undulations).

A concept was developed in order to account for these two categories. For the first type of defects all measured deviations are directly transferred via an appropriate mapping method onto the global structural model for the *In-situ Structural Evaluation*, which corresponds to the third step of the developed concept (cf. Fig. **1**).

Yet, the second type of defect usually affects not only a single ply but the overall laminate and therefore requires additional analysis effort on defect level.

In the first step the *Defect Characterisation* takes place for the relevant defects, which are to be considered within the in-situ evaluation. This step, which also provides a defect parametrisation, is performed already in the design phase, mostly experience and knowledge based, respectively.

The second step is dedicated to the *Determination of Effects on Defect Level*. This step is also to be performed in advance to the actual manufacturing and establishes the in-situ capabilities for the overall manufacturing system. Here, a database is created prior to the actual manufacturing, which is based on experimental and/or virtual (based on detailed FE models) material tests of laminates containing representative generic imperfections. This so-called Effects-of-Defects database (short EoD database) contains knock-down factors for the stiffness and strength properties of each individual layer within a laminate.

During the actual manufacturing, in the third step (*In-situ Structural Evaluation)*, a comparison of online measurement data with the EoD database takes place. This approach enables an efficient evaluation at the component level and an instant derivation of potential corrective measures. For this purpose an online fibre measurement system provides fibre angle, fibre undulations, thickness, gaps and overlaps. The observed parameters are correlated to the corresponding knock-down factors, whereby the change of failure behaviour and load redistribution due to imperfections can be represented. Surrogate models based on the EoD database enable an efficient determination of these knock-down factors during the actual manufacturing process.

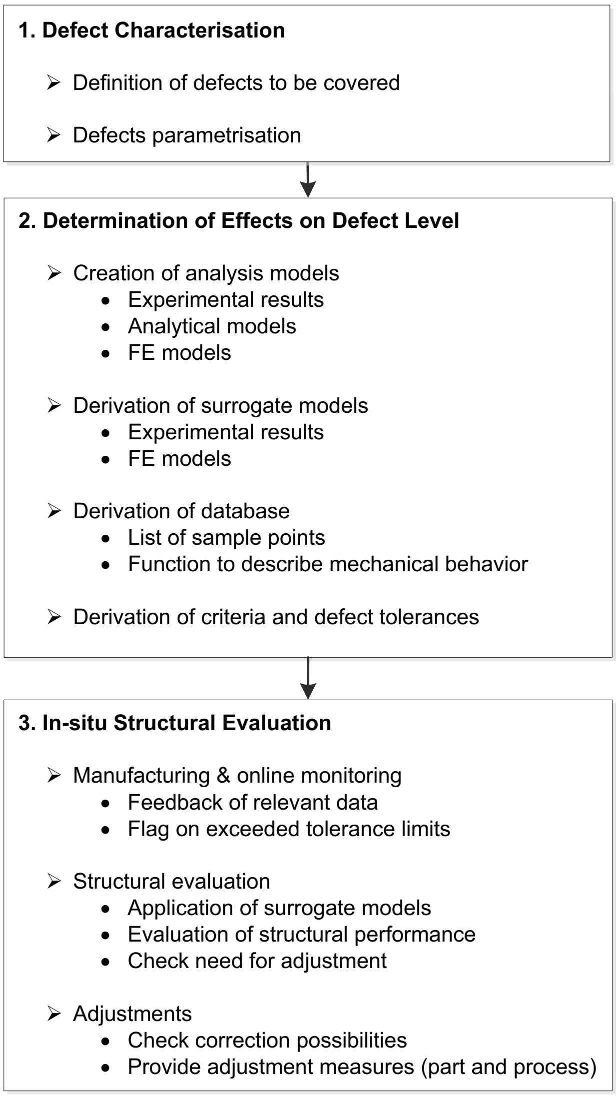

Fig. 1: Process flow for overall evaluation procedure

Within the following chapters 3 and 4 the developed methods are described for determining the effects of defects on local defect level (step 2) and performing the in-situ structural assessment on component level (step 3).

3. DETERMINATION OF EFFECTS ON DEFECT LEVEL

Current state-of-the-art software tools already provide methods such as sub-modelling or multi-scale analysis to take into account local particularities on a structural level (Llorca, et al., 2011). These methods are applicable within the detailed structural design phase in order to evaluate certain structural particularities. They can also be used during the concession phase after manufacturing in order to assess specific part deviations that have been identified by NDT. Yet, these analysis methods still require a comparably high computational effort and therefore cannot be applied for real-time analysis and evaluation during manufacturing. Also most analysis procedures are applied on single ply level and therefore don't capture the knock-down effect on adjacent plies due to local load redistribution.

An enhanced multi-scale analysis technique is presented that considers local material discontinuities on laminate level. A suitable macroscopic resolution of certain material particularities (e.g. gaps or undulations) is provided by homogenization of material properties considering 3D implication. On the basis of a specific defect parameterization effective material properties are calculated and locally assigned. This allows determining the as-built part properties for certain deviations of the fibre architecture within the laminate.

In order to provide real-time simulation capability during manufacturing the EoD database as well as surrogate models are to be generated in advance to the actual manufacturing, cf. process flow in Fig. 2. Based on given input regarding stacking, material properties and defect characteristics detailed parametric defect models are generated and used to determine the effective ply stiffness and strength values for predefined sample points. On the one hand these results are stored within the EoD database for direct use. On the other hand they further exploited for deriving surrogate models of ply stiffness and strength to enhance the EoD database.

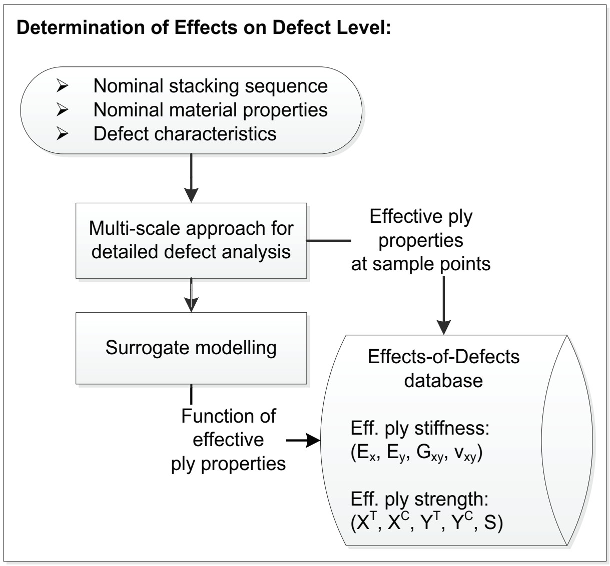

Fig. 2: Process flow for determining effects on defect level

3.1. Multi-scale approach

In general a multi-scale analysis is composed of different steps. The process starts with the generation of a local FE model, mostly called representative volume element (RVE). In this paper these local FE models are called super-elements, since material periodicity is non-existent. Fibre architecture and defect particularities are typically provided as explicit information from measurement or as generic based on a specific parameterization. Subsequently, all information is consolidated into the super-element of the defect area. Finally, virtual tests are performed in order to determine required effective material stiffness and strength parameters (Llorca, et al., 2013). These material parameters can be calculated by means of conducting a homogenization approach. Such homogenization can be performed empirically, analytically by using rules of mixture or numerically. The approach presented e.g. by (Garnich & Karami, 2005) considers the effect of localized fibre waviness in unidirectional composites but is also applicable for other types of defects, such as gaps and resulting 3D fibre undulation.

The effect of a defect on the mechanical behaviour of a local laminate depends on the respective layup and material properties (Soden, et al., 1998). Particularly, the effect of 3D effects on the material properties is of importance and requiring 3D super-element models.

In order to provide a sufficient database different super-elements have to be created for all types of relevant manufacturing defects. For this work parameterized super-element models are automatically generated and analysed using a python based framework. The defective laminate is appropriately modelled using either available measurement data or generic geometry parameters. In case of explicitly available defect data from measurement direct modelling can be performed, e.g. by importing measurement data and using advanced meshing techniques. Considering generic investigations an efficient parametrization is required for defect type, shape and size.

According to the individual manifestations of the manufacturing defects, such as gaps, overlaps or undulations, different generic geometry parameters are necessary, which represent the respective defect characteristics properly. In this context the challenge is to keep the number of parameters small enough to achieve an acceptable computational effort for deriving surrogate models, but maintain the required representation. (Garnich & Karami, 2005) and (Croft, et al., 2011) revealed that most of the relevant defects can be represented in good approximation by two parameters maximum.

In case of in-plane and out-of-plane fibre undulations the amplitude and the wavelength is commonly used to represent the geometric characteristic. As described by (Croft, et al., 2011) the geometric characteristics of gaps and overlaps can be captured in the same manner. Hence, an analogous set of characteristic geometric parameters is chosen for the gap and overlap defect.

Using the information about the nominal layup, the nominal material properties for each ply as well as the defect characteristic parameters a detailed 3D super-element model is created. Fig. 3 right depicts exemplarily a 3D FE model of a defective laminate with a missing tow in the 12th ply, which leads to a gap within the ply as well as to out-of-plane undulation in subsequent plies. The super-element is composed of 3D continuum elements, where each element row represents one ply and each colour represents a different material.

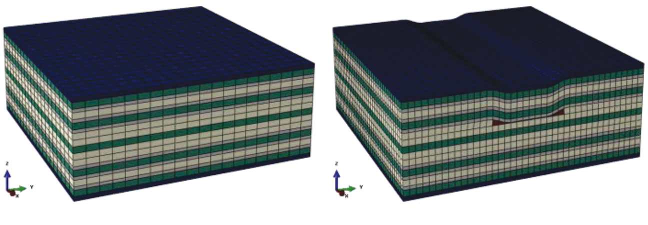

Fig. 3: 3D super-element for the nominal laminate (left) and laminate with missing tow in 12th ply (right)

The evaluation of results is the last step performed during the multi-scale analysis. In order to get the baseline, to compare against, the effective material properties of the pristine laminate (refer to Fig. 3 left) are evaluated once per layup. This calculation is reiterated for each individual defect occurring within the respective layup. Within this step the actual analysis of the local FE model and the homogenisation is conducted. To determine the effective material properties different types of boundary conditions can be used (Hill, 1963). In this work periodic uniaxial displacement boundary conditions are applied to the super-element.

Since the gap affected domain has pure resin properties, which are considerably smaller than the surrounding stiffness, this region attracts less stress. Stress concentration occurs at the edges of the gap due to a stress re-distribution, which finally changes the laminae properties compared to the pristine laminate. The effective stiffness can be computed by evaluating the individual stress components averaged for all elements of the super-element. The difference of material properties is expressed layer-wise as so-called knock-down factors. The knock-down factor determines the effect of the respective defect as the percentage of the nominal stiffness value (refer to Fig. 4) and the nominal strength value (refer to Fig. 5), respectively. For retrieving the effective strength the Tsai-Wu failure criterion is used.

For the subsequent structural evaluation and (re-)qualification only the Young's modulus in fibre direction (Ex), the Young's modulus in transverse direction (Ey), the in-plane shear modulus (Gxy) and the in-plane Poisson's ratio (Nuxy) is needed. The same applies to the strength properties. Just the tensile and compressive strength in fibre direction (XT, XC), in transverse direction (YT, YC) and the shear strength (S) are important. By simulating the same layup with various defect configurations a set of sample points is generated, which is in turn used for the subsequent surrogate modelling.

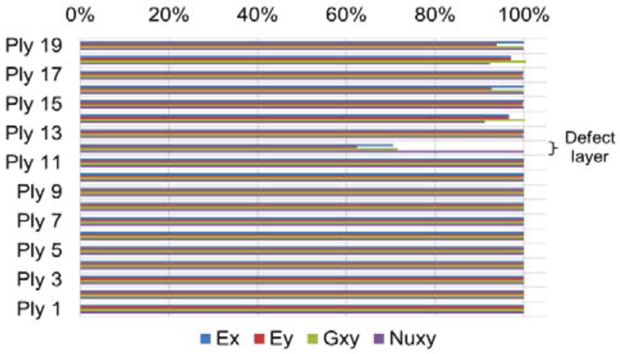

Fig. 4: Knock-Down Factors of the nominal stiffness material properties

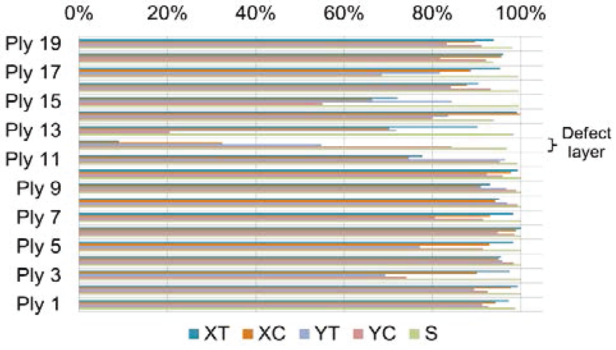

Fig. 5: Knock-Down Factors of the nominal strength material properties

3.2. Surrogate Modelling

Serving the overall requirement for real-time assessment the potential of surrogate models is exploited. For this purpose individual surrogate models are derived for each knock-down factor in order to evaluate the effects of defects during the actual manufacturing phase.

The principle workflow makes use of the open source framework OpenTurns (Anon., n.d.) with a python implementation. This framework comprises several so-called designs of experiments (DoE) to create appropriate sample points for subsequent surrogate modelling. The Latin Hypercube sampling technique is widely used for engineering problems, as discussed e.g. by (Manan & Cooper, 2009). It has also been proven to be suitable for this work to create an adequate DoE for the required parameter space and computational effort for all design points.

Regarding the subsequent step of surrogate modelling several techniques are available to solve engineering problems, cf. (Forrester, et al., 2008) and (Forrester & Kean, 2009). The most common surrogate modelling techniques are the Polynomial Regression, the Radial Basis Functions, the Kriging and the Support Vector Regression. Due to their different approaches for creating a surrogate model they also differ in accuracy, robustness and suitability (Nik, et al., 2014).

Because of the good relation between efficiency and accuracy the Kriging algorithm is chosen to generate the surrogate model describing the effects of defects on the local level. The parameter space of these models on defect level consists of the affected defective layer (first parameter) and the width of the defect (second parameter).

Fig. 6 exemplarily depicts the visualization of a resulting surrogate model for the knock-down factor of the laminate property Ey, i.e. the Young's modulus of the laminate in y-direction). Depending on the defect location, described by the position of the defect layer within the layup, and the defect width the knock-down factor for Ey varies between 0.68 and 1.0.

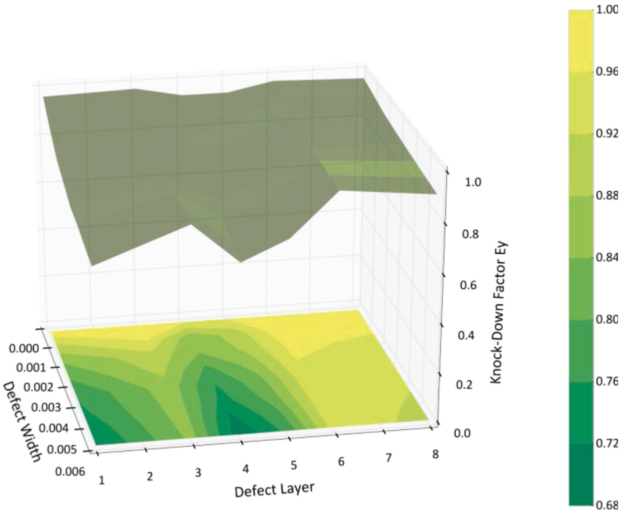

Fig. 6: Surrogate Model – visualization of the surrogate model of the knock-down factor for Ey of the laminate

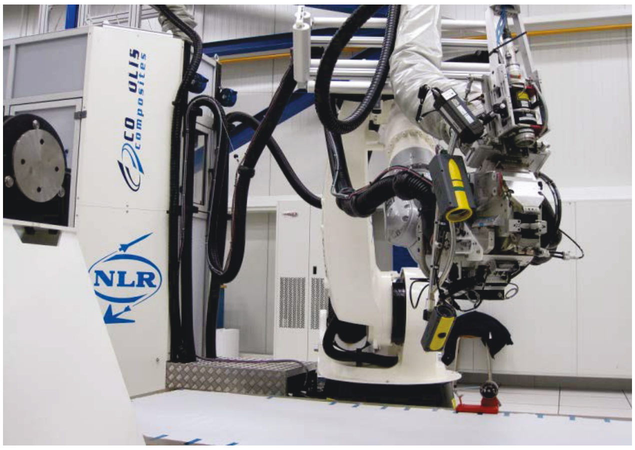

Fig. 7: AFP robot at NLR with integrated 3D optical measurement system

4. IN-SITU STRUCTURAL EVALUATION

Depending on the geometrical complexity of the part as well as the selected manufacturing technology and composite material different type of deviations can occur. In case of fibre deposition by AFP variations in fibre orientation, thickness, gaps, overlaps as well as undulations or folds are relevant imperfections. Within this paper the in-situ structural evaluation process is presented as actual performed during dry fibre placement at the facility of the Netherlands Aerospace Center (NLR), depicted in Fig. 7. A customized laser scanning system from Loop Technologies is mounted directly onto the AFP head measuring thickness profiles and identifying deviations of fibre architecture. Characteristic parameters are directly provided as input for the in-situ structural evaluation process. Within this paper the focus is given to the analysis of detected gaps.

The principle methodology enabling the in-situ structural evaluation is provided in Fig. 8. During the actual manufacturing the as-built model is used for re-evaluation and re-qualification purposes. It is continuously updated with new manufacturing data coming from the online monitoring system. The main focus is laid on the assessment of the change in structural response in terms of global deformation and failure behaviour. The as-built structure is compared to the ideal as-design structure,

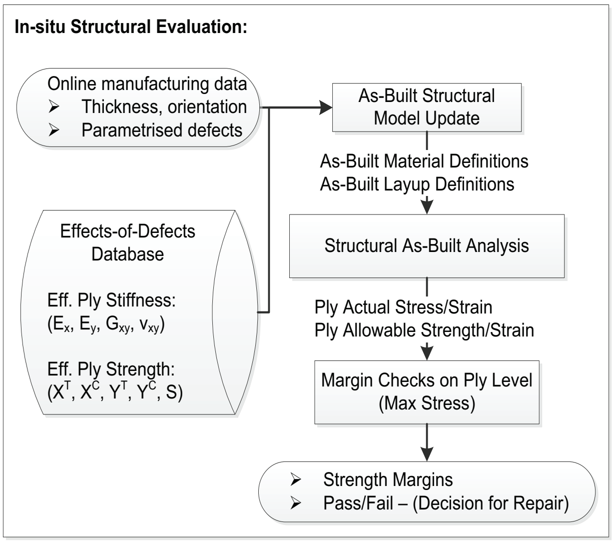

Fig. 8: Process flow – In-situ Structural Evaluation

which is the baseline. Consequently, a decision is made whether the structural quality of the actual component is still acceptable or not.

Following, the in-situ structural evaluation is demonstrated by means of a wing cover of an aircraft manufactured by AFP technology. In Fig. 9 the as-design FE model of the wing cover is illustrated. The wing cover is composed of generic varying layups, which are assigned to different regions of the wing skin as indicated by individual colours. The baseline wing cover, which serves as reference structure, is assumed to have no material inhomogeneity or deviation of fibre architecture. It is evaluated with respect to structural allowable (i.e. stiffness, strengths). Starting point is a global structural check. Before manufacturing stress analysis is available for the idealized preliminary sized model of the wing skin providing expected margins of safety without any defects.

In Fig. 10 the structural response for a representative load case is depicted. For this example the region of the wing cover near to the wing root is exposed to tensile loading. With increasing distance from the wing root the loading condition is more compression dominated.

Within this paper Equation 1 is used for the calculation of the margins of safety (MoS).

$$\text{Margin of Safety} = \frac{\text{Allowable Stress}}{\text{Applied Stress}} - 1. \tag{1}$$

In order to determine the margins of safety failure indices are calculated, assuming the 'Maximum Stress' failure criterion and first ply failure as catastrophic event.

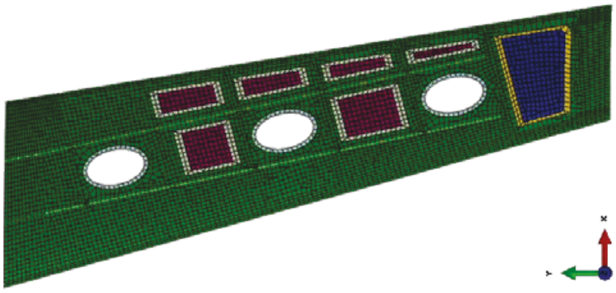

Fig. 9: Idealized preliminary sized model of the wing skin – colours indicating varying layup definitions

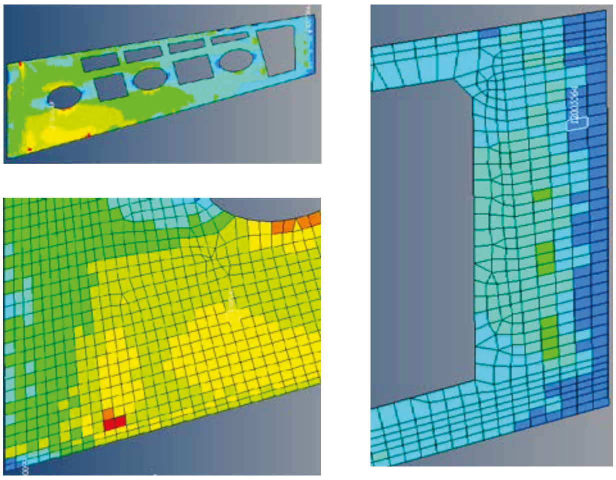

Fig. 10: Baseline GFEM check - tension dominated area (lower left) and compression dominated area (right)

As described in section 3, the effective material properties of the pristine laminate (baseline laminate) are determined prior to the actual manufacturing. The layup depicted in Fig. 3 left corresponds to the green coloured domain of the wing skin in Fig. 9. The smallest MoS in the baseline model equals to zero, which is acceptable when considering conservatisms of the analysis technique.

A missing tow defect, which complies with a 6.35 mm wide gap within the layup, is introduced on purpose to demonstrate the in-situ capabilities of fibre monitoring and structural evaluation. The defect location corresponds to the yellow tensile stressed domain in the wing skin (cf. Fig. 10). Due to the sensitivity of the measurement system a large number of smaller gap and overlap features are detected, as shown in Fig. 11. The missing tow is identified and the characteristic defect parameters are determined by the measurement system. Here the length and the width of a defect are always related to the actual fibre orientation, i.e. the length of the defect corresponds to the fibre direction and the width of the defect is assigned to the transverse direction.

In the next step the respective structural characteristics of the as-built model are compared with the nominal (baseline) structural specifications. In order to update the actual stress/ deformation state or the actual local material properties of the simulation model feedback and mapping methods are applied in real-time including an update of the corresponding material properties of all finite elements affected by the defect.

The following changes are introduced to the baseline GFEM to account for the detected 6.35 mm wide gap caused by a dropped tow at ply 12 (refer to Fig. 3 right):

- For each ply additional material ply level property entries are created. Based on the effective lamina strength and stiffness properties calculated from the DFEM (refer to section 3).
- For each finite element referencing the newly created effective material properties an additional composite section property entry is created.
- Within the new section property entries, an effective ply thickness is calculated for the defective ply (in this case ply 12) to account for gap.
- These new section properties are assigned to the elements incorporating the region of the gap.

The knock-down factors for the material stiffness and strengths, which are used to calculate the effective material properties for the respective defective layup, are provided in Fig. 4 and Fig. 5, respectively.

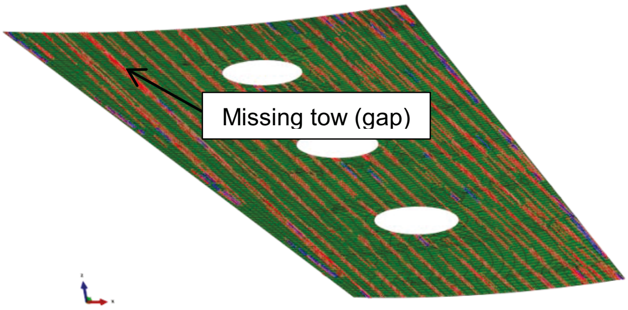

Fig. 11: Gap (red) and overlap (blue) on wing cover detected by 3D measurement system

The effective ply thickness of an affected finite element is calculated as follows:

Baseline Ply Area: $$A_{Bl} = [\text{Element Width}] * [\text{Ply Thickness}], \tag{2}$$

Gap Area: $$A_{Gap} = [\text{Gap Width}] * [\text{Ply Thickness}], \tag{3}$$

Eff. Ply Thickness: $$t_{eff} = \frac{[A_{Bl} - A_{Gap}]}{[\text{Element Width}]}. \tag{4}$$

It should be noted that this approach smears the effect of the local gap across a wider area than the 6.35 mm gap due to the underlying GFEM with coarse element sizes. By over representing the size of the defect, this approach builds in a degree of conservatism when assessing the effects of the defect.

The global structural check is repeated on the as-built wing skin to check margins of safety under consideration of defects. The stress analysis is performed applying the same load case but effective material properties for affected elements. Within the global structural check the effects of stress redistribution to regions of pristine material are examined.

In Fig. 12 material effort is compared between the baseline GFEM and as-built GFEM. The results indicate no significant change in the global maximum material effort as a result of this defect introduced. However, the peak locations of the material utilization vary due to the stress re-distribution. For the baseline structure the highest material effort (80% to 100%) is found in the orange and red coloured regions, respectively. Whereas, the missing tow defect leads to an increased material utilization of 100% at the cut-outs and a decreased effort of the material (80%) at stringer positions.

A local structural check is carried out on all elements, which are affected by the defect. Again the maximum stress values, the failure indices and the margisn of safety for in-plane shear and tension in fibre direction are determined layer-wise. It is found that all MoS are positive owing to large reserve strength. The results indicate that for the given load case and defect all checked margins remain acceptable. Tab. 1 summarizes the results obtained by the local check – stress analysis.

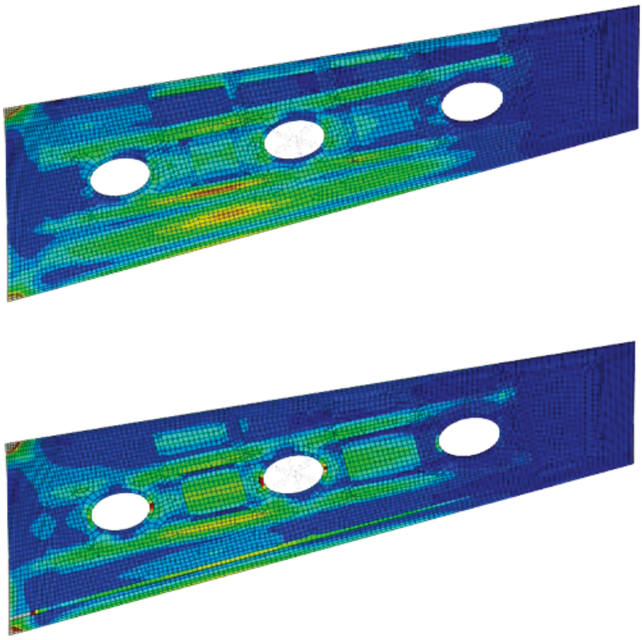

Fig. 12: Comparisons of material effort between baseline GFEM (top) and as-built GFEM incl. defect (bottom)

5. CONCLUSION AND OUTLOOK

Within the paper a new overall concept and underlying methods were developed for an efficient in-situ evaluation of manufacturing defects by assessing their actual effect on the structural part performance already during AFP manufacturing. In detail a step-wise approach was introduced comprising detailed preparation analysis and efficient online analysis in order to provide required in-situ evaluation capability. Procedures were described for appropriate defect characterisation by means of gaps. Multi-scale analysis methods were described for determining local knock-down factors for all plies of an affected laminate taking into account local load redistribution. Additionally, surrogate modelling techniques were exploited and integrated into a framework. As a result the effects-of-defects database was generated capturing the effects of gaps, overlaps or undulations on local laminate level in form of discrete values or functions.

Furthermore, it was explained how actual online measurement data of the fibre deposition can be used to evaluate occurring manufacturing deviations already during production. The procedure was demonstrated for an industrial aeronautic wing cover application. To this the global impact of local manufacturing imperfections was assessed. On the one hand significant load redistribution was observed leading to higher material effort in defect-free areas of the part. On the other hand all checked margins remain acceptable for given load case and defect, thus enabling to continue manufacturing without costly rework.

Therefore this paper describes a key technology to enhance future manufacturing and concession processes by automated defect assessment and decision making with respect to required process or part corrections. High benefits are particularly expected when applied to early manufacturing steps in order to adjust before provoking further unnecessary costs within subsequent manufacturing steps.

In order to ensure full industrial capability further research and technical developments are required. Experimental testing is recommended for increased understanding of physical behaviour of interacting defects and validation on structural level. Also further demand is identified for efficient and reliable monitoring systems capturing relevant defects inside parts. Moreover, additional effort is required to provide closed-loop automated feedback to the manufacturing facility in case of required process and part correction.

	Baseline GFEM		As-Built GFEM		Relative Difference	
PLY	MoS_XXt	MoS_XY+	MoS_XXt	MoS_XY+	MoS_XXt	MoS_XY+
Ply-01	5.187	-	5.023	-	-0.163	-
Ply-02	-	12.404	-	12.289	-	-0.115
Ply-03	14.794	-	14.399	-	-0.395	-
Ply-04	11.286	-	10.750	-	-0.536	-
Ply-05	14.921	-	14.653	-	-0.268	-
Ply-06	-	152.659	-	150.806	-	-1.852
Ply-07	15.064	-	14.649	-	-0.415	-
Ply-08	11.487	-	10.783	-	-0.704	-
Ply-09	11.556	-	10.688	-	-0.869	-
Ply-10	-	12.927	-	12.695	-	-0.232
Ply-11	11.696	-	8.674	-	-3.021	-
Ply-12	11.767	-	0.582	-	-11.185	-
Ply-13	15.587	-	13.566	-	-2.022	-
Ply-14	-	13.232	-	12.008	-	-1.224
Ply-15	15.743	-	10.693	-	-5.050	-
Ply-16	11.997	-	10.255	-	-1.741	-
Ply-17	15.886	-	14.530	-	-1.356	-
Ply-18	-	224.000	-	202.802	-	-21.198
Ply-19	5.734	-	5.067	-	-0.668	-

Tab. 1: Comparisons between baseline GFEM and as-built GFEM including gap defect

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