FROM AS-DESIGNED TO AS-BUILT ANALYSIS USING AN MULTISCALE APPROACH AND MODEL UPDATE

Falk Heinecke*

Structural Mechanics, GermanAerospace Center (DLR), Lilienthalplatz 7,
Braunschweig, 38108, Germany
falk.heinecke@dlr.de
http://www.dlr.de

Tobias Wille

Structural Mechanics, GermanAerospace Center (DLR), Lilienthalplatz 7,
Braunschweig, 38108, Germany
tobias.wille@dlr.de
http://www.dlr.de

Abstract

MAAXIMUS is a European funded project enhancing process and evaluation techniques in order to maximize process efficiency at reduced costs and production time due to less material consumption, higher reproducibility, less energy, less waste and less rework. The methodology presented in this paper focuses on the automated fibre placement (AFP) technique in particular on the assessment of deviations within the composite laminate, e.g. fibre curvature, gaps and overlaps. The goal is to determine the effective material properties in terms of stiffness and strength that are related to these manufacturing deviations, to enable a so called as-built structural analysis and evaluation. A multiscale approach is exploited, which is dedicated to assess the difference in mechanical performance of as-designed and as-built structures. The effective stiffness and strength are calculated by numerical analysis on the local level and homogenized for the macro level. This way the macro level structural response can be calculated computationally efficient.

The results give evidence that the investigated manufacturing deviations have a significant effect on the stiffness and in particular on the strength. A decrease in stiffness and strength for an increasing fibre curvature has been observed from the finite element analyses. The model update, performed on the overall structure by assigning the effective properties to respective regions, reveals a change in the structural behaviour compared to the reference. This study is not exhaustive, further investigations and validation with experimental data is to be done.

Keywords Model update, Multiscale, AFP, Curvature, Gap, Overlap.

1. INTRODUCTION

Within current composite part development and manufacturing processes a disproportional high effort is implied in order to find optimal process parameters and to meet required qualities and tolerances of high performance light weight structures. The necessity of new approaches and methodologies for improving and consolidating current disjoint processes was pointed out by Wille *et al.* (2013). Within this context the MAAXIMUS project addressed the development of an advanced tool to enable as-built analyses of complex structures, with the goal to maximize process efficiency at reduced costs and production time due to less material consumption, higher reproducibility, less energy, less waste and less rework.

The presented work illustrates how an as-built analysis for the AFP composite manufacturing process can be established. The AFP process is characterized by a high grade of automation and flexibility, which allows short cycle times, continuous accuracy and part quality as well as complex shaped parts with complex layup, Lukaszewicz *et al.* (2012). But with the new degrees of freedom associated to this technology, like fibre steering, the possibility to create complex shapes and complex layups, several other challenges emerge. Therefore the need for an as-built analysis of AFP manufactured structures is inherent in the technology itself. In this work a method is proposed on how common AFP technology related manufacturing deviations can be considered and what influence they have on the mechanical performance of the structure.

Variations in the mechanical performance are caused by e.g. machine deviations, material variation and laminate designs that require ply angle transitions and cutting of tows. The most fundamental manufacturing deviation, which not only occurs during the AFP but also in woven fabrics and textiles, is the fibre undulation in-plane or in thickness (also called fibre waviness). In terms of the AFP process the fibre waviness is mainly related to fibre steering and other manufacturing deviations, which might occur, like gaps and overlaps. In Figure 1 a window-panel is shown made from CFRP using fibre steering, facilitated by AFP.

* Corresponding Author

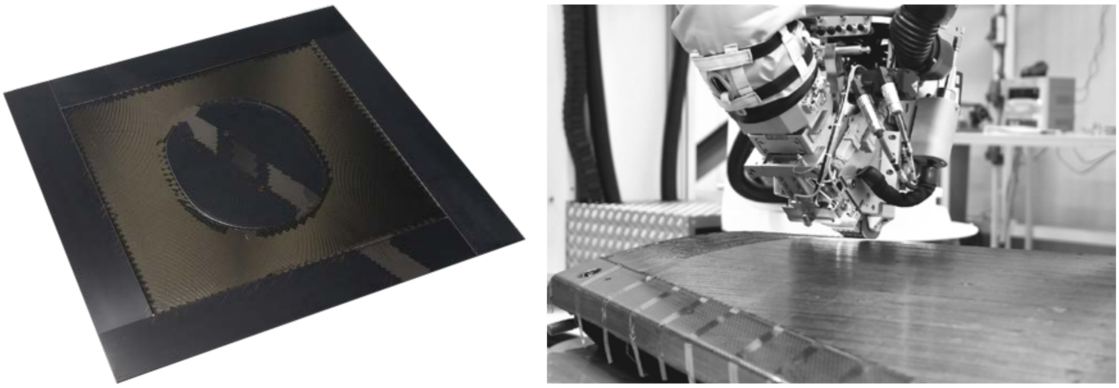

Figure 1. Composite window-panel using the AFP technique (right) with steered fibres.

For more than 20 years various research groups have investigated this type of deviation in composites. Telegadas and Hyer (1992), Wisnom (1994), Piggott (1995) and Hsiao and Daniel (1996a;b) were almost the first determining the effect of fibre waviness on the mechanical properties of unidirectional composites. But research is still ongoing (e.g. ref. Sawicki and Minguett (1998); Garnich (2005); Pankow *et al.* (2009); Pansart *et al.* (2009); Lemanski *et al.* (2013); Croft *et al.* (2011); Garnich and Karami (2004; 2005). Due to emerging new manufacturing technologies (like AFP) and materials, the investigation of manufacturing deviations gathered further attention. Related research often is performed as a direct consequence of fibre steering with variable stiffness laminates (Sawicki and Minguett (1998); Fayazbakhsh *et al.* (2013); Falcó *et al.* (2014a; b)). The results of all these investigations give good indication that there is a non-negligible effect on the strength and also on the stiffness of the composite laminate induced by fibre waviness and other manufacturing deviations. Furthermore it is shown that stiffness effects of manufacturing deviations can be represented rather accurate using contemporary numerical approaches (Pansart *et al.* (2009); Fayazbakhsh *et al.* (2013); Falcó *et al.* (2014b); Garnich and Karami (2004; 2005). However, despite all the effort spent on this research topic, the determination and prediction of failure still challenges the analysts. A clear approach or indication for knock-down factors for laminates containing defects is currently not present. There is also a need for efficient models and analysis methods enabling the in-situ evaluation of manufacturing deviations during manufacturing as well as a concurrent engineering within the overall composite design process.

Within this context the scope of this work is to evaluate the effect of fibre curvature on stiffness and strength to evaluate the change in the structural response which is associated to fibre steering or manufacturing deviations.

For this purpose the actual fibre information, measured (e.g. optical fibre monitoring) and/ or simulated (e.g. draping or AFP simulation), is to be correlated to the corresponding as-design analysis model, in this case an FE model of the structure to be manufactured. Compared to the geometric dimensions of the structure the magnitude of the actual fibre curvatures are relatively small. A strategy is needed to efficiently incorporate manufacturing deviations into the structural analysis with the aim to predict the structural performance of the actual manufactured part. A schematic of such a process is illustrated in Figure 2, which is a development from Kärger and Kling (2013).

Starting point is an as-design analysis model (cf. Figure 2 - upper right), that results for example from a conceptual sizing. In order to account for manufacturing deviations, e.g. fibre angle deviation and fibre curvature several multiscale analyses with different characteristics of the respective manufacturing deviation are performed using a local FE models (cf. Figure 2 - lower right), which incorporate all mesoscopic details on lamina level. This can be done either in advance or during the actual structural analysis. The results of these multiscale analyses are used to create parameter curves, that show the knock-down of the material properties depending on the respective geometrical deviations (cf. Figure 2 – lower left). The section properties of each finite element will be adjusted accordingly, if applicable. This process step is called feedback (in the literature often referred to as model update). Depending on the magnitude of the manufacturing deviation, the actual material properties (as-built) might tremendously deviate from the pristine properties (as-design). Finally, a fast re-evaluation and re-qualification of the structural response is enabled.

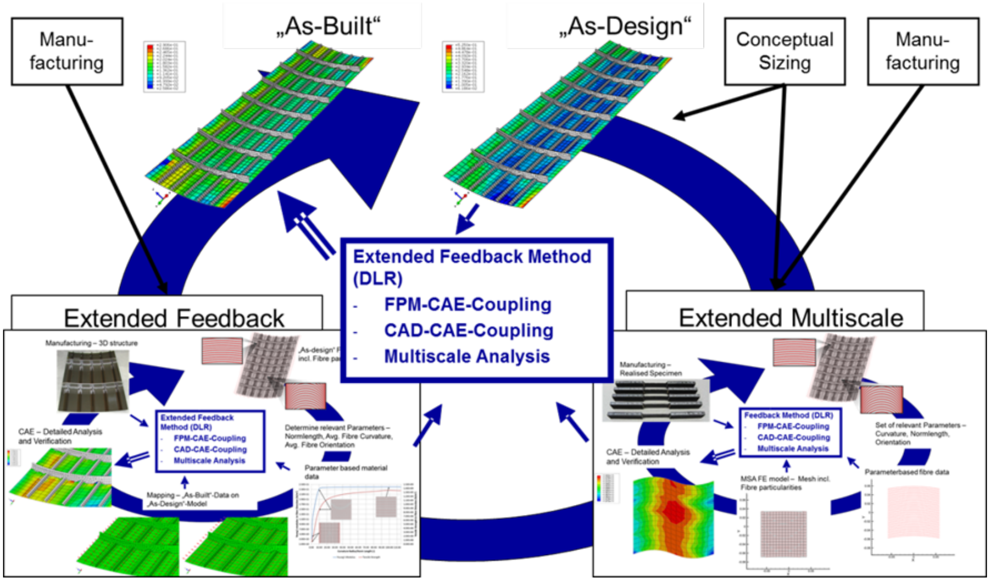

Figure 2. Schematic of process to capture manufacturing defects by means of the FEM.

2. Problem Definition

Due to the composite part application within the MAAXIMUS project the in-plane fibre curvature manufacturing deviation is investigated in this work. Yet the proposed methods are rather general and therefore not limited to this example. The curvature is a measure for the magnitude how much a geometric object is deviating from being straight. In other words, it describes how the fibre angle is changing along a specific fibre path length. The fibre curvature radius R is depending on the fibre curvature κ [°/m] and can be obtained by:

$$\boldsymbol{R} = \frac{\mathbf{1}}{\boldsymbol{\kappa}} \tag{1}$$

For the sake of simplicity an unstiffened single curved panel is defined as test problem. This panel is depicted in Figure 3. The structure is partly covered by strongly steered fibres, which are created using the hyperbolic tangent (tanh) function. Thus, not every region of the layer is influenced and to be adjusted, respectively.
This test problem is generic and dedicated to illustrate the capabilities of the proposed method. The corresponding geometric specifications are provided in Table 1.

Table 1. Characteristic parameters of the panel geometry.

Geometric Parameter	Value
Length	2,00 m
Arc length	2.00 m
Radius	4.00 m

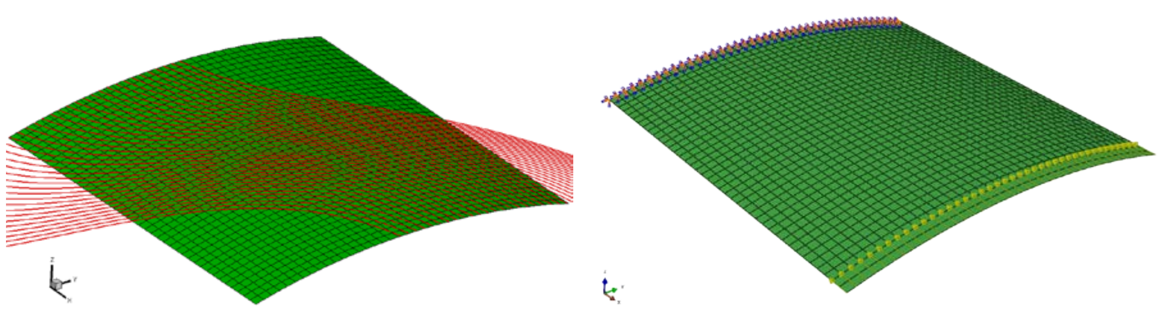

Figure 3. Test problem - Generated fibre data (left) on clamped single curved unstiffended panel under 10,000 N compression loading.

Each layer of the composite layup is composed of the same material, whose respective parameters are itemized in Table 2.

Table 2. Composite layup - Material parameters.

Material Parameter	Value
Longitudinal Modulus	2,40E+11 N/m^2
Transversal Modulus	7,00E+09 N/m^2
Shear Modulus	5,00E+09 N/m^2
Poisons Ratio	0.35
Longitudinal Strength	1,35E+09 N/m^2
Transversal Strength	4,20E+07 N/m^2
Shear Strength	4,00E+07 N/m^2

The initial composite layup of the panel is defined as $[45/-45/0/90/45/-45/0/90]_s$. The first 45° oriented layer will be adjusted according to the created fibre data. Finally, the layup turns into [S†/-45/0/90/45/-45/0/90/90/0/-45/45/90/0/-45/45].

3. Methods

This section is dedicated to briefly introduce the multiscale analysis (MSA) method, which is FEA based, and the feedback method, which is used to enable the as-built analysis of structures containing manufacturing induced deviations. Material particularities like fibre undulations on the meso-scale (lamina level) or imperfections on an even smaller material scale co-determine the structural response on the macro-scale (laminate/ structure level). The MSA considers local ply discontinuities and provides a suitable macroscopic resolution of composite ply deviations like fibre undulations, gaps and overlaps. The effective stiffness and strength on the macroscopic level is calculated by numerical analysis on the local level and subsequently homogenized onto the macro-scale. This way the structural response on macroscopic level can be calculated computationally efficient.

In terms of a multiscale analysis a detailed analysis of the local model is conducted. The MSA exploits a so called homogenization approach to efficiently capture the effects on material level by means of effective properties on the structure level. Such a homogenization can be performed empirically, analytically or numerically. Garnich (2005) and Garnich and Karami (2004; 2005) present a numerical homogenization approach to consider the effect of localized fibre waviness in unidirectional composites.

3.1. *Multi-Scale Analysis (MSA)*

A similar, but slightly adapted, approach like it is proposed by Fayazbakhsh *et al.* (2013) and Falcó *et al.* (2014b) is used in this work. Correspondingly, the following assumptions and simplifications were made:

- Ideal fibre distribution,
- The simulation model is shell based (using layered elements),
- The finite element mesh is regular and structured discretized.

The multiscale approach is composed of different steps. The principle workflow of the applied method is depicted in Figure 4.

Based on the fibre information available on the global level (provided by measurement and/ or simulation) sets of parameters are determined, which are relevant for creating parameterized local FE models, containing detailed fibre particularities. The individual fibre orientations and fibre curvatures are determined for each element on the macroscopic level (cf. Figure 4 – upper right). The information about manufacturing deviations (e.g. curvature radius – cf. Figure 4 – lower right) is mapped onto a high density finite element mesh (cf. Figure 4 – lower middle).

† Abriviation, indicating a steered layer (spatial variable fiber orientations as well as material properties)

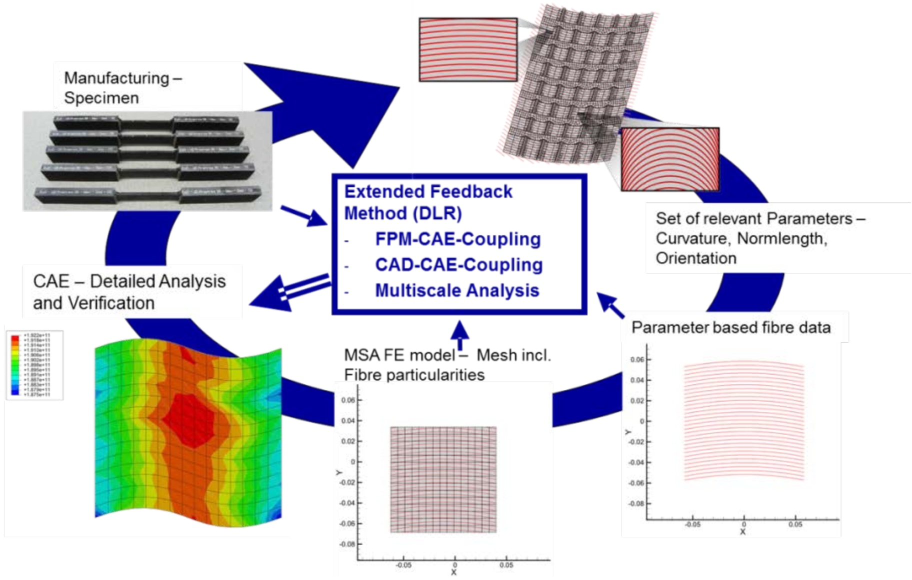

Figure 4. MSA - Principle workflow of applied method.

Finally, unidirectional unit-strains are sequentially applied, which is exemplarily by applied shear in (cf. Figure 4 – lower left). The effective stiffness can be computed by averaging the stresses occurring in the local model for each applied deformation. In order to perform the numerical homogenization, boundary conditions have to be applied to the model by definition. For this purpose different types of boundary conditions can be used (Hill (1963)). In this work periodic displacement boundary conditions (cf. Figure 4 – lower left) are applied to the local FE model.

Almost the same approach is used to determine the effective strength. Theoretically any failure criterion can be evaluated to compute the effective strength. In this work the Tsai-Wu criterion is applied to the local model to retrieve the failure indexes of each finite element of the local FE model. The maximal failure index determines the residual strength of the material.

The effect of these deviations on the material properties on lamina level is exemplarily illustrated in Figure 5. The Young’s modulus and tensile strength in fibre direction, respectively, is plotted vs. the normed characteristic curvature parameter of the fibre. This parameter is determined by dividing the actual curvature radius of the fibre through the distance (called norm length) of the two intersection points of the fibre with the respective finite element.

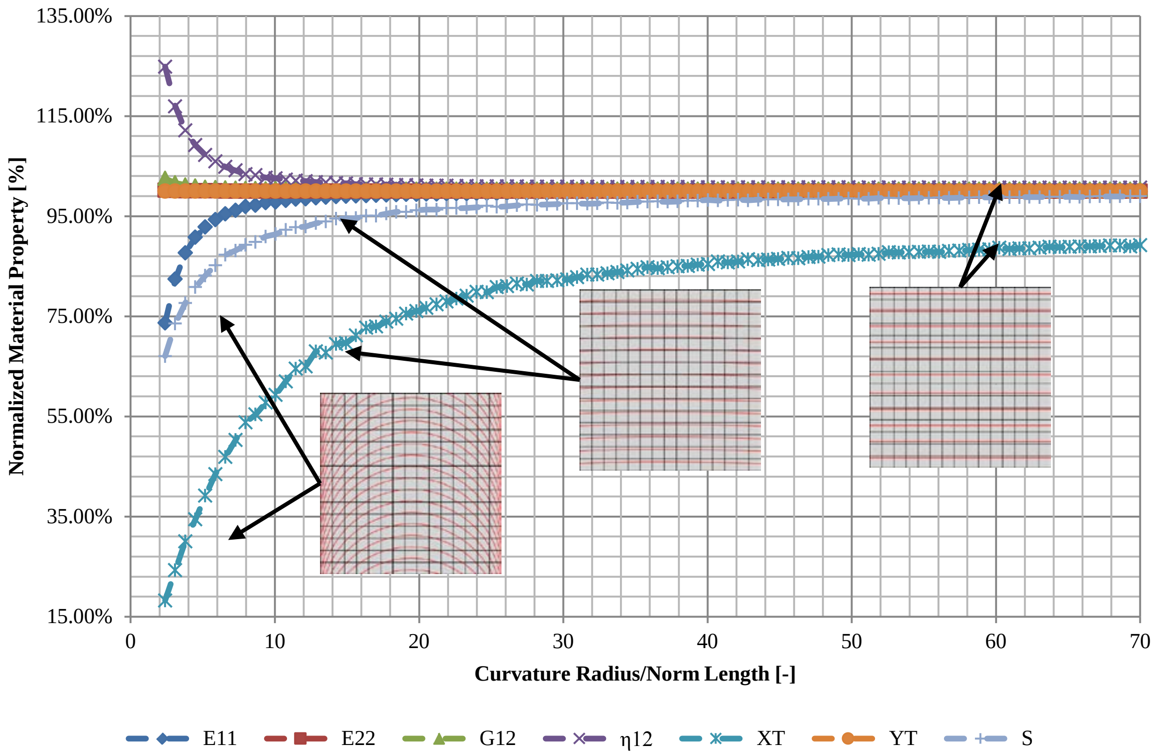

Figure 5. Effect of fibre curvature with varying magnitudes on tensile (in fibre direction) modulus and strength.

It is found that the transverse modulus (E22) and the transverse strength (YT) as well as the shear modulus (G12) are not affected by any magnitude of fibre curvature. For the remaining material properties, longitudinal modulus (E11), Poisson's ratio (η12), longitudinal strength (XT) and shear strength (S), there is a strong non-linear influence on the lamina material properties.

For strongly steered layups fibre curvatures of 0.2 [°/m] and above in magnitude likely occur, which yields to a tremendously reduction in material properties. The highest decrease in longitudinal stiffness is determined to be approximately 25%. The fibre curvature causes longitudinal strength reduction of almost 85%.

3.2. *Feedback*

Once the interpolation curves, like they are shown in Figure 5, are derived they can be subsequently used to adjust the material properties of the structure model, using the feedback method. The core capability of the feedback method is the as-design to as-built data transformation. This part of the overall process (cf. Figure 2) is very challenging, because it is performed in 3D space. An illustration of the as-design to as-built data transformation step is provided in Figure 6.

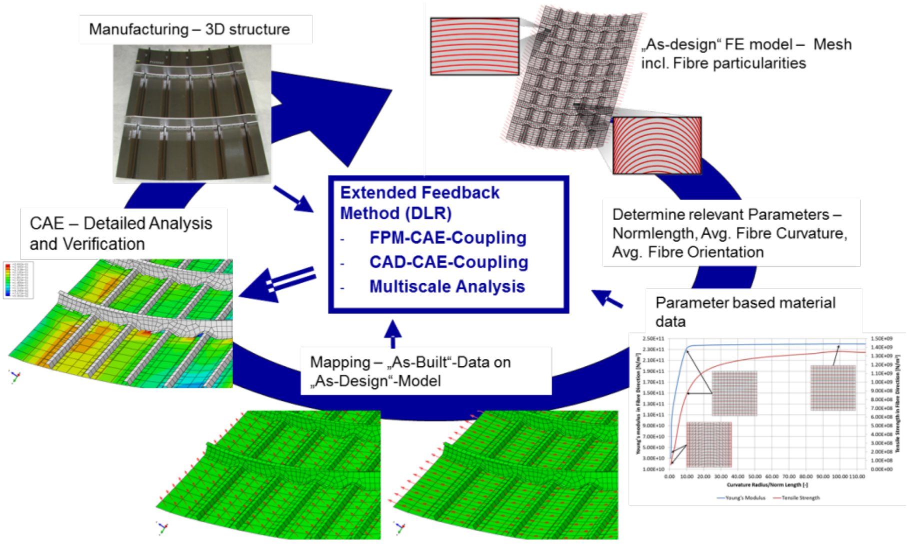

Figure 6. Feedback – Workflow of as-design to as-built transformation.

The starting point is again the initial (as-design) FE model. An algorithm is determining all relevant geometric parameters (e.g. average curvature, average fibre angle…) for each finite element of the model (cf. Figure 6 – upper right), which are affected by the fibre particularities. By means of these geometric parameters, determined in advance, the respective material properties in terms of stiffness and strength can be evaluated by exploiting the interpolation curves (cf. Figure 6 – lower right, cf. section 3.1). A binary search tree, in particular a kd-tree, is exploited to identify the fibres that are located within or in the proximity of a finite element. The orientation and the curvature of all fibres, located within an element, will be averaged. During this mapping the finite element properties a new material orientation, stiffness and strength is assigned (cf. Figure 6 – lower middle). Finally, the resulting as-built is re-evaluated (cf. Figure 6 – lower left), in order to determine the performance of the manufactured part.

4. Results

The relevant results to be observed are initial as well as adjusted material orientations and curvatures for the affected layer (cf. section 2). Stress distributions and failure behaviour is evaluated also. Figure 7 illustrates the mapping result in terms of the material orientation. Due to the curved path of the generated fibres the material orientation within the affected domain is varying in a range from 15° to 60°.

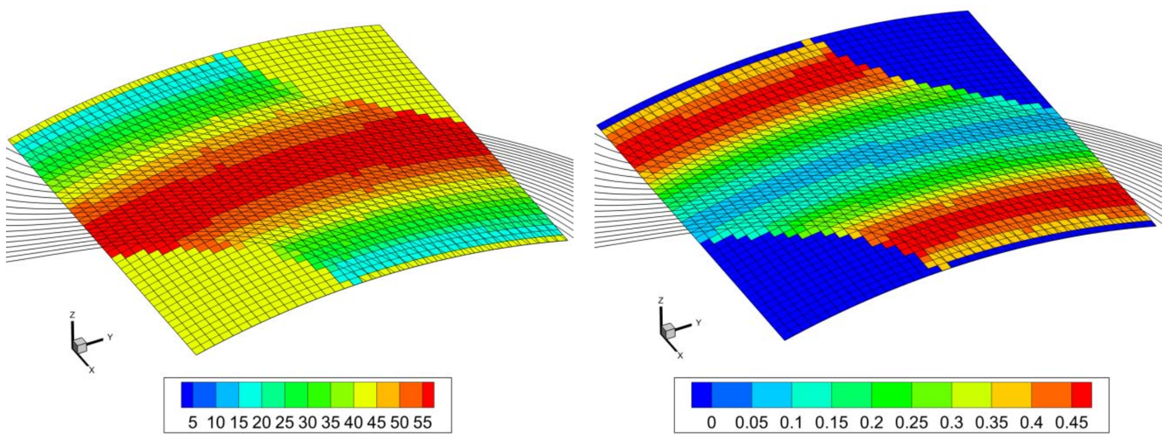

Figure 7. Test problem - Material orientation [°] (left) and fibre curvature κ [°/m].

The yellow coloured regions remain unaffected with a material orientation of 45°, as initially specified. Due to the symmetrical shape of the used function (cf. section 2) the mapping result is also symmetrical. The influence on the fibre curvature κ is also depicted in Figure 7. The occurring fibre curvatures are changing, which is caused the varying gradient of the hyperbolic tangent function. The highest variation occurs in the edge regions of the structure. Thus the highest curvature values are located there (indicated red in Figure 7). Consequently, the fibre curvature radius is varying in a range from 10 m in the centre region of the panel up to to 2 m,in the panel edge region.

Depending on the curvature magnitude the stiffness and strength is decreasing. The longitudinal stiffness reduction is illustrated in Figure 8. It turns out that the occurring fibre curvature leads to a reduction of the longitudinal modulus by approximately 0.1% (cf. Figure 8 left - orange coloured region) to 0.7% (cf. Figure 8 left - light blue domain). This stiffness reduction might be negligible w.r.t. to the global structural behaviour.

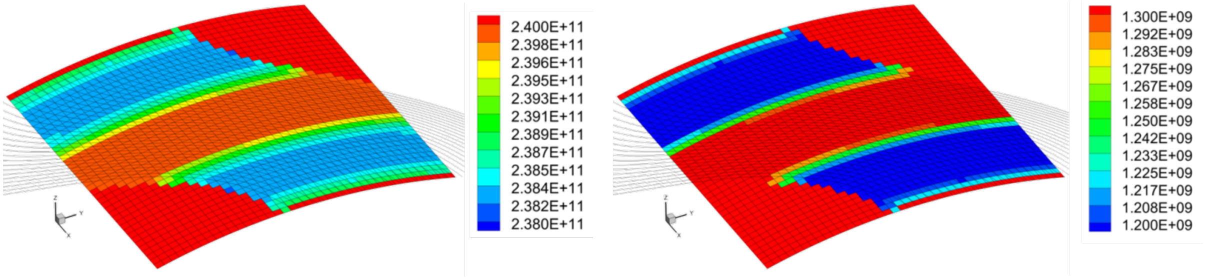

Figure 8. Test problem - Longitudinal modulus E11 [N/m^2] (left) and longitudinal strength XT [N/m^2].

In contrast to the marginal stiffness reduction the fibre curvature has a significant influence on the strength of the material (cf. Figure 8 right). A reduction in longitudinal strength of almost 9% in the upper and lower region of the panel is found. Since the ply angle variation in the panel centre region is not significant the longitudinal strength stays unaffected.

The re-evaluation of the adjusted FE model reveals a change within the stress response, which is related to the actual stiffness of the structure, and on the failure behaviour, which is strongly related to the actual structural strength. As mentioned before, the effect of the fibre curvature on the resulting structural stiffness is marginal. Thus, it is expected to have a small impact on the stress response related to this adjustment. At the first glance the longitudinal stresses shown in Figure 9 are surprising, considering the prior statement. However, the stress distribution is absolutely reasonable, since the fibres are no longer equally oriented in 45° direction, but steered with spatial varying fibre orientations (cf. Figure 7). Due to the compression loading (cf. section 2) in longitudinal direction (global x-direction) the stress re-distributes according to the fibre course. Hence, the panel edges regions attract higher stresses than the centre region. This is because the material orientation in the centre region of the panel (50°-60°) is less aligned with the load direction than the panel edge regions (15°-30°).

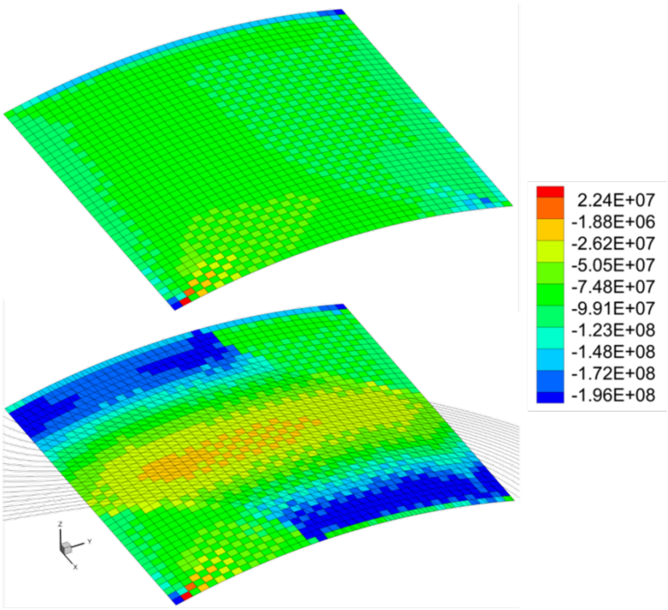

Figure 9. Test problem - Longitudinal stress distribution [N/m^2] of initial model (upper) and adjusted model.

In order to investigate the effect of strength reduction on the structural response one of the Tsai-Wu failure criterion is applied. The distribution of material utilization induced by stresses is depicted in Figure 14. Expectedly, the distribution of structural reserve is changing. Except for boundary effects the initial structural reserve is almost uniformly distributed (cf. Figure 14). The material effort computed is approximately 16%. The stress distribution within the adjusted FE model implies that the failure indices will increase in the regions, where stresses are more concentrated, compared to the initial model. This expectation is approved. It turns out that the results related to structural failure correlates to the changed stress distribution. All regions, which are unaffected by the fibre steering remain at a level of 16% material effort. By contrast, the material utilization at the panel edge regions is increased by 4%.

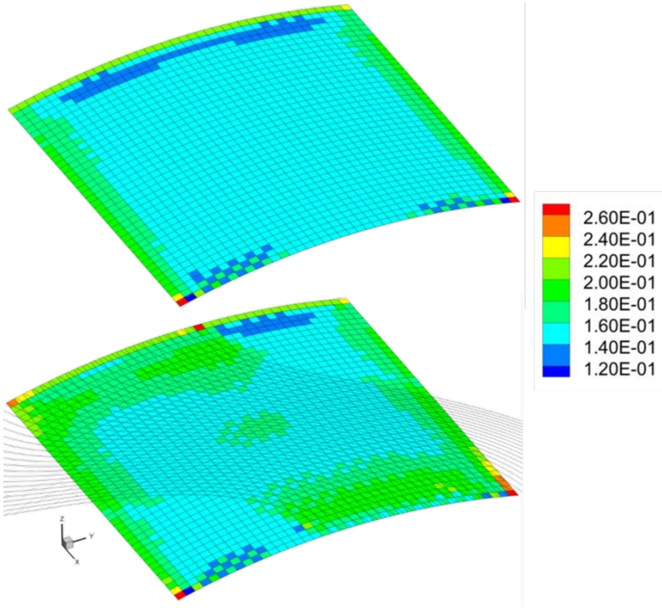

Figure 10. Test problem - Failure indices according to Tsai-Wu of initial model (upper) and adjusted model.

The results give good indication that the investigated manufacturing deviations may have a significant effect on the strength and the stiffness also. Since fibre waviness leads to stress concentrations it will most certainly become eminent for other loading conditions like compression or shear. However, more validation is needed to provide additional insight in the manufactured laminates with misalignments.

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References

Croft K., Lessard L., Pasini D., Hojjati M., Chen J., and Yousefpour A., Composites : Part A Experimental study of the effect of automated fiber placement induced defects on performance of composite laminates, *Compos. Part A*, **42**, 2011, pp. 484–491, Available online at http://dx.doi.org/10.1016/j.compositesa.2011.01.007.

Falcó O., Mayugo J.A., Lopes C.S., Gascons N. and, Costa J., Variable-stiffness composite panels: Defect tolerance under in-plane tensile loading, *Composites Part A: Applied Science and Manufacturing*, **63**, 2014, pp. 21–31, Available online at http://dx.doi.org/10.1016/j.compstruct.2014.05.005.

Falcó O., Mayugo J.A., Lopes C.S., Gascons N., Turon A. and, Costa J., Variable-stiffness composite panels: As-manufactured modeling and its influence on the failure behavior, *Composites Part B: Engineering*, **56**, 2014, pp. 660-669, Available online at http://dx.doi.org/10.1016/j.compositesb.2013.09.003.

Fayazbakhsh K.,Nik M. A., Pasini D. and Lessard L., Defect layer method to capture effect of gaps and overlaps in variable stiffness laminates made by Automated Fiber Placement, *Composite Structures*, **97**, 2013, pp. 245-251, Available online at http://dx.doi.org/10.1016/j.compstruct.2012.10.031.

Garnich M. R. and Karami G., Finite Element Micromechanics for Stiffness and Strength of Wavy Fiber Composites, *J. Compos. Mater.*, **38**, 2004, pp. 273–292, Available online at http://dx.doi.org/10.1177/0021998304039270.

Garnich M. R., Localized Fiber Waviness and Implications for Failure in Unidirectional Composites, *J. Compos. Mater.*, **39**, 2005, pp. 1225–1245, Available online at http://dx.doi.org/10.1177/0021998305048748.

Hsiao H.M. and Daniel I.M., Effect of fiber waviness on stiffness and strength reduction of unidirectional composites under compressive loading, *Compos. Sci. Technol.*, **56**, 1996, pp. 581–593, Available online at http://dx.doi.org/10.1016/0266-3538(96)00045-0.

Hsiao H.M. and Daniel I.M., Elastic properties of composites with fiber waviness, *Compos. Part A Appl. Sci. Manuf.*, **27**, 1996, pp. 931–941, Available online at http://dx.doi.org/10.1016/1359-835x(96)00034-6.

Hill R., Elastic properties of reinforced solids: Some theoretical principles, *Journal of the Mechanics and Physics of Solids*, **11**, 1963, pp. 357-372, Available online at http://dx.doi.org/10.1016/0022-5096(63)90036-X.

Karami G. and Garnich M. R., Effective moduli and failure considerations for composites with periodic fiber waviness, *Compos. Struct.*, **67**, 2005, pp. 461–475, Available online at http://dx.doi.org/10.1016/j.compstruct.2004.02.005.

Kärger L.; Kling A., As-built FE simulation of advanced fibre placement structures based on manufacturing data, *Composite Structures*, **100**, 2013, pp. 104–112, Available online at http://dx.doi.org/10.1016/j.compstruct.2012.11.024.

Lemanski S. L., Wang J., Sutcliffe M. P. F., Potter K. D., and Wisnom M. R., Modelling failure of composite specimens with defects under compression loading, *Compos. Part A Appl. Sci. Manuf.*, **48**, 2013, pp. 26–36, Available online at http://dx.doi.org/10.1016/j.compositesa.2012.12.007.

Lukaszewicz D. H.-J. a., Ward C., and Potter K.D., The engineering aspects of automated prepreg layup: History, present and future, *Compos. Part B Eng.*, **43**, 2012, pp. 997–1009, Available online at http://dx.doi.org/10.1016/j.compositesb.2011.12.003.

Pankow M., Waas A. M., Yen C., and Ghiorse S., Composites : Part A A new lamination theory for layered textile composites that account for manufacturing induced effects, *Compos. Part A*, **40**, 2009, pp. 1991–2003, Available online at http://dx.doi.org/10.1016/j.compositesa.2009.08.021.

Pansart S., Sinapius M., and Gabbert U., A comprehensive explanation of compression strength differences between various CFRP materials: Micro-meso model, predictions, parameter studies, *Compos. Part A Appl. Sci. Manuf.*, **40**, 2009, pp. 376–387, Available online at http://dx.doi.org/10.1016/j.compositesa.2009.08.021.

Piggott M.R., The effect of fibre waviness on the mechanical properties of unidirectional fibre composites: A review, *Compos. Sci. Technol.*, **53**, 1995, pp. 201–205, Available online at http://dx.doi.org/10.1016/0266-3538(95)00019-4.

Sawicki A. and Minguett P., The effect of intraply overlaps and gaps upon the compression strength of composite laminates, in *39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, 1998, pp. 744–754, Available online at http://dx.doi.org/10.2514/6.1998-1786.

Telegadas H. K.and Hyer M. W., The Influence of Layer Waviness on the Stress State in Hydrostatically Loaded Cylinders: Failure Predictions, *J. Reinf. Plast. Compos.*, **11**, 1992, pp. 127–145, Available online at http://dx.doi.org/10.1177/073168449201100202.

Wille T., Kärger L., Hein R., *Composite Process Chain Towards As-Built Design*, Available online at http://dx.doi.org/10.1007/978-3-642-29190-6_15, pp. 199-210, In: M. Wiedemann and M. Sinapius, *Adaptive, tolerant and efficient composite structures*, Springer Berlin Heidelberg, Research Topics in Aerospace, 2013.

Wisnom M. R., The Effect of Fibre Waviness on the Relationship between Compressive and Flexural Strengths of Unidirectional Composites, *J. Compos. Mater.*, **28**, 1994, pp. 66–76, Available online at http://dx.doi.org/10.1177/002199839402800105.