DESIGN OPTIMIZATION OF AN UNCONVENTIONAL CFRP AIRCRAFT PANEL STIFFENER BASED ON MANUFACTURABILITY CRITERIA OF INTEGRATED FIBER PLACEMENT PROCESS ANALYSIS

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Abstract

This paper introduces a global optimization methodology that comprises structural analysis in conjunction with manufacturability examination of the aircraft components based on in-house developed automated fiber placement (AFP) system. Target point of the investigation is an unconventional grid stiffened carbon fiber reinforced plastic (CFRP) fuselage panel with additional multi-curved local stabilizers (stiffener peaks) that are located between diagonal grid stiffeners. The optimization task is formulated to reach global minimum weight of the panel under combined loading scenarios with respect to composite material failures, stability and manufacturability of stiffener peaks based on AFP system. Presented methodology solves the multi-disciplinary problem and offers producible unconventional configurations with adequate mechanical performance and weight savings based on production limits and objectives.

1. Introduction

Expanding demands for volume-production of CFRP structures induce advanced composite manufacturing technologies such as AFP systems offering efficiency by means of production time [1]. Nevertheless production limitations, especially for composites, can confront the engineers with redesign necessity in terms of manufacturability of the optimized components. Moreover, production effects on the composite materials may cause considerable imperfections on CFRP structures and influence the optimization results regarding stability analysis [2]. Considering manufacturing imperfections by means of AFP, gaps have substantial effects on structural performance [3] and are most commonly identified after conclusive structural designs. Hence, significances of manufacturing technologies and their restrictions on optimization of composite structures [4] have to be taken into account at each design phase, especially for unconventional structures that require excessive iterations in optimization process.

This paper presents a novel optimization approach – as a part of ongoing research of the project *High Performance Production of CFRP Structures* (HP CFK) – that associates structural optimization with manufacturability of components and restriction of imperfections such as tow gaps regarding AFP system in order to avoid recurring design phases. Within this context a new AFP concept will be introduced which is highly adaptable to complex curved surfaces.

2. Grid-Stiffened HP CFK panel

Various stiffener topologies adjusted to loading conditions at different sections of the fuselage can improve efficiency in terms of weight saving [6], similar to natural structures which have risen from evolution. Considering the fact that, slanted stiffened topologies offer increased performance under shear loading conditions [7], the presented panel has a concept of slanted-grid topology around the window sections of fuselage where effective shear loading occurs and is combined with traditionally stiffened panels in circumference direction. The investigated panel design consists of three major parts presented in Figure 1 as follows, intersection points, slanted stiffeners and local stabilizers called as stiffener peaks. Each stiffener component comprises of foam material [8] and reinforced with unidirectional carbon fibers [9], [10].

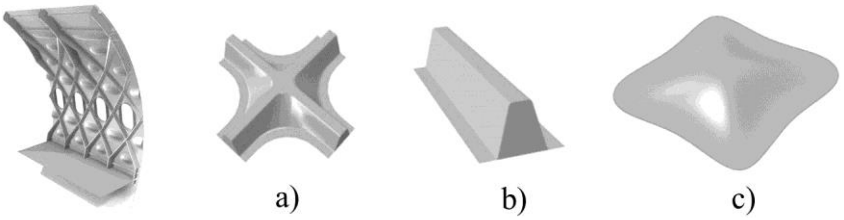

Figure 1. Panel and its components: a) Intersection point. b) Slanted stiffener. c) Stiffener peak

The manufacturing process starts with the prepreg-skin being placed on a 2D surface by AFP and then being transformed into 3D by a flexible forming process (Figure 2). Foam of stiffener peaks are placed and processed as well in AFP followed by the location of the more complex grid-stiffener foams. Draping process on slanted stiffeners and intersection points using innovative textile-concept is carried out and afterwards slanted stiffeners are infused and bonded to prepreg skin via co-curing process in autoclave.

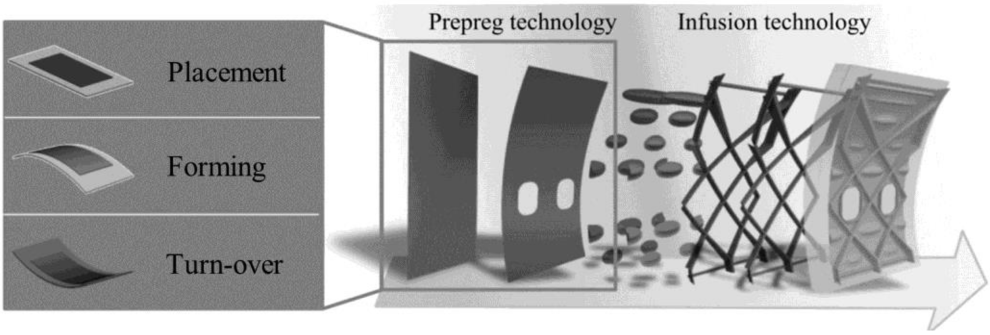

Figure 2. Production phases of HP CFK panel with combined prepreg and infusion technology

3. Automated fiber placement system

In this research project, a new AFP head is developed. The different components are in-house developments and differentiate quite significantly with today’s AFP systems. Its advantages are increased laying velocities of approximately 3 m/s and the application of a form flexible compaction device with a decreased minimal tape length. Thus, the AFP head is not only able to place slit tapes on plane fuselage skin with high productivity but also on complex geometries such as the described stiffener peak.

3.1. Machine characteristics

The head is designed for placing four tows of conventional 6.35 mm material width. Each tow velocity is independently adjustable. Therefore four tow paths exist each with a material storage, transportation, cutting and compaction devices. To adapt to different surface conditions like stiff metal molds or the more elastic foams, the compaction device is separated in four force-controlled compaction segments, allowing an additional radial displacement. The applied cutting device is able to cut slit tapes lower than a minimum placement length of 100 mm. The entire concept of the AFP head and its components is scalable to a multiple of 4 tows.

3.2. Manufacturability criteria

The geometric characteristics presented in Figure 3 represent the most important criteria for design optimization regarding restrictions of the compaction device. The AFP head processes 1/4” (6.35 mm) slit tape. Between each tow and compaction segment a gap of 0.2 mm exists because of tow guidance.

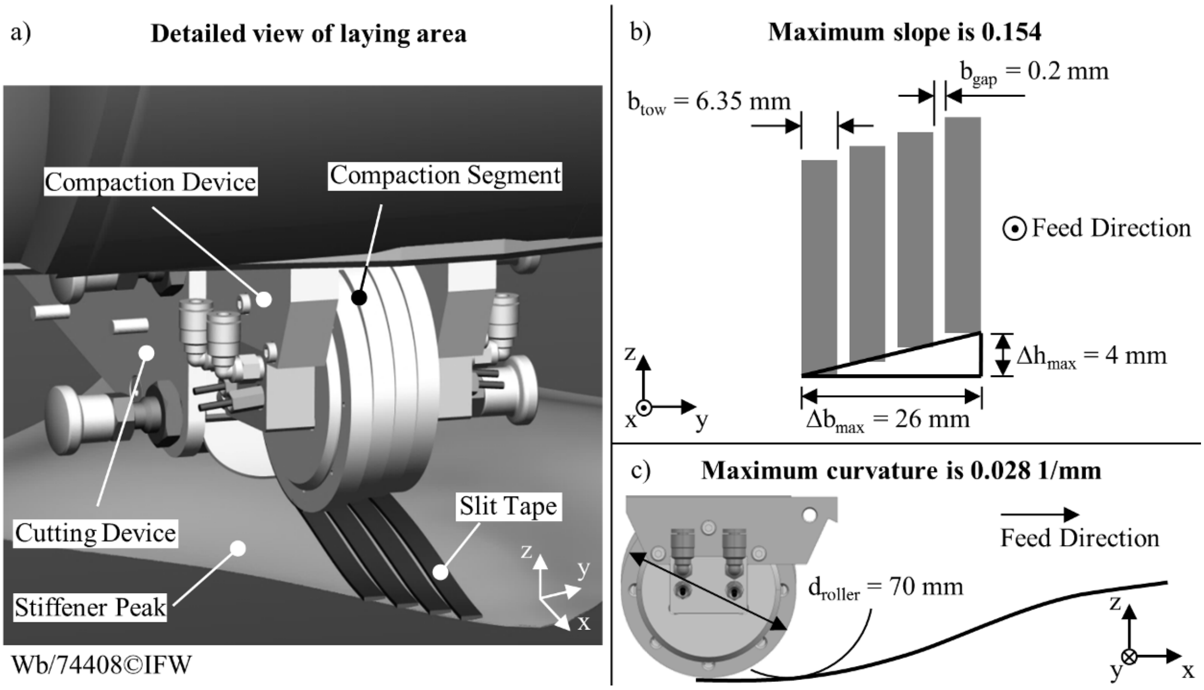

Figure 3. Geometric characteristics of the compaction device of HP CFK AFP head

Each segment is able to perform a radial displacement of up to 4 mm. With an overall width of 26 mm the resulting maximum slope of the compaction device is 0.154 across feed direction (b). Another criterion derived from the compaction device is the curvature (c). The segment diameter of 70 mm allows a maximum curvature of 0.029 1/mm for concave arched surfaces. These three criteria, the gap, the maximum slope and the maximum curvature are taken into account within the optimization procedure.

4. Design optimization of aircraft panel

The goal of the investigation is to obtain the best structural configuration that satisfies design requirements such as stability, damage tolerance, material failures and manufacturability criteria on stiffener peaks, offering minimum panel mass with best allowable stacking sequences on stiffeners whose variables are restricted to 0°, +45°, -45°, 90° with a fixed thickness of 0.125 mm for each layer. Lay-up of the skin is kept constant with $[+45, 0, -45, 90]_{sym}$ and each layer has a thickness of 0.250 mm. In order to increase efficiency in terms of computation time, all manufacturing output is approximated by a response surface based on radial basis functions precisely presented in [11].

4.1. Response surface generation

Radial basis function artificial neural networks (RBF-ANN) method based on biological process of neurons of a brain outputs a linear combination of weighted radial basis functions in this case Gaussian functions to get a non-linear surrogate model offering faster approximation compared to other mapping methods. The surrogate model generation represented in Figure 4 is carried out according to training data sets that contain input samples regarding optimization parameters of the FE panel model and corresponding output sets containing maximum tow gaps, ascending slope, and curvature information belonging to the surface of stiffener peaks.

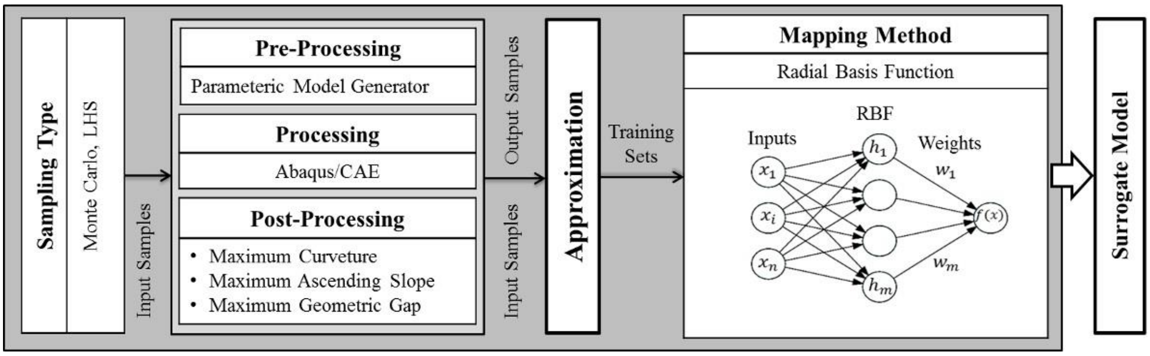

Figure 4. Response Surface Generation of manufacturability output of stiffener peaks

4.2. Optimization methodology

The optimization framework combines manufacturability outputs from surrogate models with FE analysis during the optimization process by adding and weighting mapping functions of objectives $C^{opt}(F(u))$ and constraints $C_l^{=/<}(f(u))$ such as manufacturability and structural restrictions, for fitness evaluations, C of each individual represented in equation (1) where u presents system parameters.

$$C(F(u), f(u)) = w_0 C^{opt}(F(u)) + \sum_{l=1}^{n=+n_<} w_l C_l^{=/<}(f_l(u)) \qquad (1)$$

5. Manufacturability analysis

The herein investigated unconventional peaks have an excessive sensitiveness in terms of manufacturability. Hence, to follow manufacturing requirements of each stiffener peak within optimization, response surface approximation is performed before structural simulation. By means of this chronology, computational time is reduced with fast approximation and by termination of structural analysis that has non-producible configurations.

5.1. Analysis of surface slopes and curvatures

Computation of surface slopes and curvatures is performed by projecting partitioning lines on the stiffener peak according to the global fiber placement direction. Distances between lines are set to a single tow width including segmentation spacing on the compaction roller. By this means, the neutral fiber line can be obtained between two partitioning lines representing fiber path borders. Ascending surface slopes are computed along the vertical direction of neutral fiber path. Allowable curvature or minimum radius is iteratively computed regarding neutral fiber lines by using spline function of the developed simulation environment.

5.2. Geometric gaps between tows

Based on the same methodology, geometric gaps, *d1, d2* illustrated in Figure 5 are analyzed at the points that are lying on the intersection of vertical partitioning lines and projected borders of tows with assumption of infinitesimal material strains vertical to fiber direction.

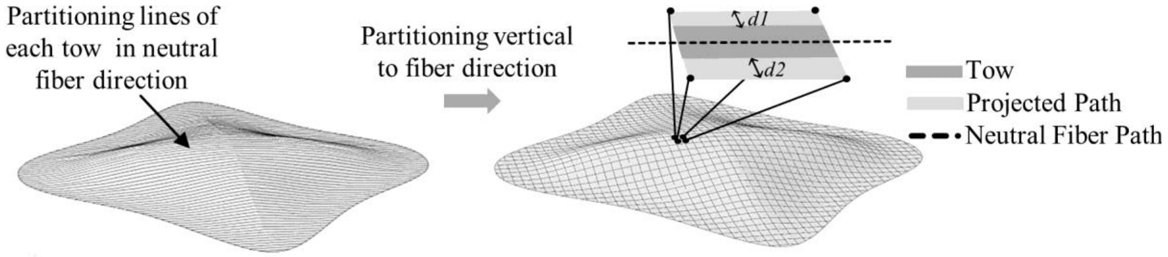

Figure 5. Projection of fiber path and geometric gap estimation based on neutral fiber path and tow width

6. Simulation model and design variables

An automated parametric panel generation tool with an AFP interface was developed in order to investigate all possible structural configurations and evaluate buckling values, material failures under combined load cases presented in Table 1 within a large design scope.

6.1. Finite element model and load cases

In this primary investigation of the novel panel topology, the FE model is generated without window sections. Nevertheless optimized panel topology will be used as an initial configuration for further window cut-out investigations. Skin is modeled with shell elements whereas stiffener sections contain shell element nodes coupled with solid elements of foam. In order to realize aircraft fuselage deformations on panel level, periodic boundary conditions are applied at the edges of the FE model illustrated in Figure 6. Different loading scenarios and corresponding failure analyses are automatically performed in optimization.

Load Case	**Loading Type**	**Analysis Type**	**Cabin Pressure [mbar]**	**Axial Loading, $n_{x,x}$ [N/mm]**	**Shear Loading, $n_{x,\theta}$ [N/mm]**
1	Cabin Pressure	Static	1200	120.0	-
2	Maneuver	Static	600	60.0	-86
3	Lateral Gust	Static	600	197.0	-1.0
4	Lateral Gust	Static, Buckle	-	-	-86
5	Maneuver	Static, Buckle	-	-137.0	-67.0

Table 1. Load cases and origins of loading conditions with corresponding analysis type in optimization process

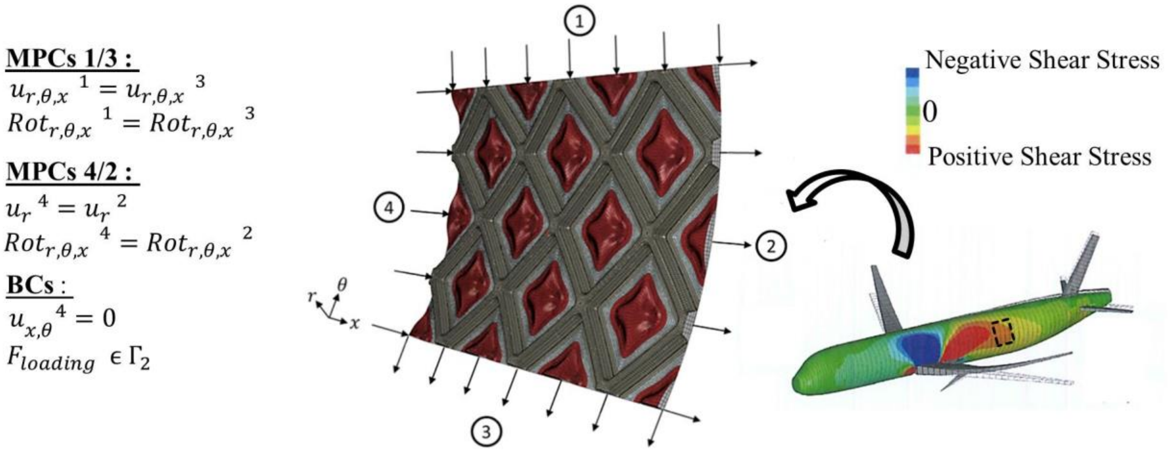

Figure 6. A FE model with multi point constraints (MPCs) and shear stress distribution on an aircraft model

6.2. Parametric model generation, design variables and constraints

One of the main characteristics of the generation tool is to perform meshing strategies according to user defined partitioning interface in order to obtain regular quad elements on CFRP sections and better shape quality at solid foam sections presented in Figure 7.

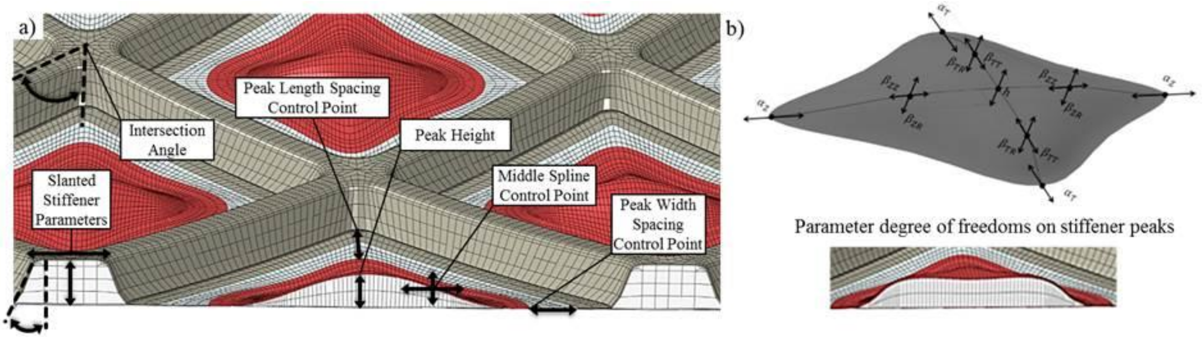

Figure 7. a) Design variables of stiffeners, b) A random configuration of panel with detailed illustration of stiffener peak and its parameters

Stiffener peak configurations are generated using spline functions consisting of seven independent design variables. Slanted stiffener parameters are also included together with intersection angle in the parametric design scope presented in Table 2.

Parameter Type	Number of Parameters	Design Variables
Diagonal stiffener profile	3	Height, top width, inclination angle
Stiffener peak topology	7	Spline control points see Figure 7
Intersection	1	Intersection angle
Lay-up parameters of peaks	2	Number of plies, orientation of plies
Lay-up parameters of slanted stiffeners	2	Number of plies, orientation of plies

Table 2. Definition of parameter types and design variables of FE panel model

The lay-up parameters are optimized with an interface to the table of allowable lay-ups created by the lay-up generator based on number of layers and design requirements stated at [5] such as symmetry and balance condition where at least 8 % of fibers have same orientation, not more than four plies having the same direction could be stacked in a sequence and in order to minimize impact effects orientation of outermost layers are restraint to ± 45.

No	Constraint Type	Constraints
1	Allowable Strain in each Load Case , ε	$\varepsilon < \varepsilon_{\max}$
2	Reserve Factor Load Case 4 , RF_1	$RF_1 > 1$
3	Reserve Factor Load Case 5 , RF_2	$RF_2 > 1$
4	Maximum Ascending Slope, m	$m < 0.154$
5	Maximum Curvature, κ	$\kappa < 0.028$ 1/mm
6	Maximum Tow Gaps, d	$d < 0.5$ mm

Table 3. Structural and mechanical constraints of design optimization

The damage tolerance requirement of the panel is satisfied by maximum strain $\varepsilon_{\max}$ condition in each load case (see Table 1). Buckling of the structure is not allowed under load cases 4 and 5. Manufacturability constraints (4, 5 and 6) in Table 3 are assigned according to requirements illustrated in Figure 3 and approximated by response surface method.

7. Results and conclusions

The structural evolution is set to 25 populations, with 50 offspring per generation and infinite lifespan in the optimization environment. During the automated optimization approx. 1250 topologies were modelled and analyzed with respect to buckling and static loading combined with response surface approximation of AFP manufacturability analysis on peaks.

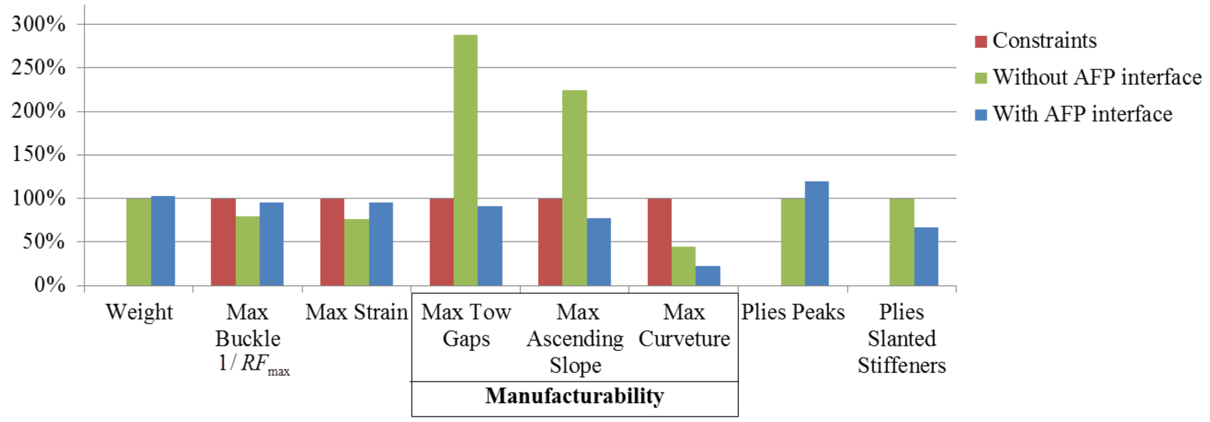

Figure 8. Comparison of optimization results with and without AFP interface

In order to observe the influences of manufacturability constraints, a further optimization without these restrictions (4, 5 and 6 in Table 3) was carried out and the results are compared in Figure 8. Significant discrepancies are observed in the manufacturability of unconventional peaks on both optimized panels. An inverse ratio between number of plies and volume of foams concerning each optimization results is obtained. It is caused by the restrictions of the AFP process on the peaks as well as lower density of foam material compared to prepreg. The presented methodology offers unconventional configuration that can be manufactured with considerably less tow gaps illustrated in Figure 9 based on AFP process and adequate structural performance with 2 % of weight increment compared to results without AFP interface.

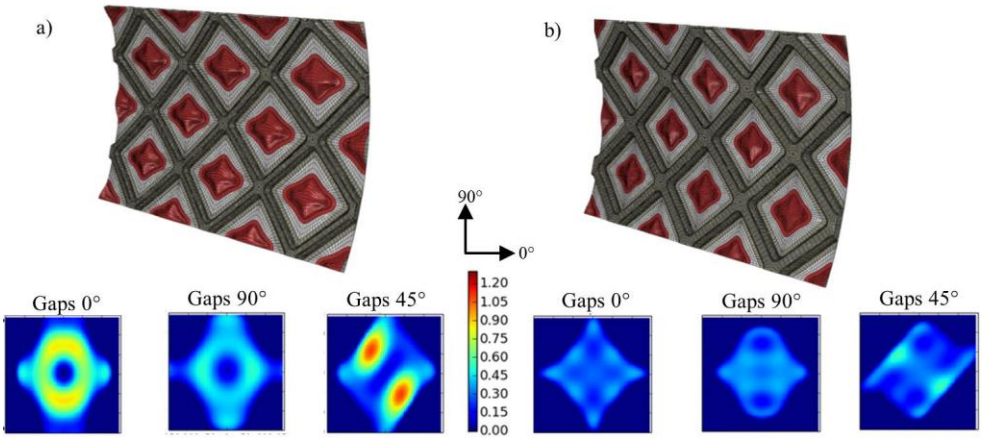

Figure 9. Pure geometric gap illustration on peaks of optimized panels with b) and without AFP interface a)

The presented approach utilizes the high potential of composite materials based on currently available technology offering required manufacturability and desired reduction on imperfections such as gaps and can be improved further by integration of drapibility of slanted stiffeners. Potential of the panel can be extended by adding window cut-out sections.

Acknowledgements

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