INVESTIGATION OF MULTI-MATERIAL LAMINATES FOR SMART DROOP NOSE DEVICES

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Abstract

For the application of laminar flow at commercial aircraft wings the high-lift devices at the leading edge play a major role. Since conventional leading edge devices like slats do not comply with the high surface quality requirements needed for laminar flow, alternative concepts must be developed. Besides the conventional Krueger device which provides laminar flow on the upper side of the airfoil and an insect shielding functionality, smart droop nose devices are currently being investigated. However, the research on such morphing devices which can deform to a given target shape and provide a smooth, high-quality surface has to give answers to questions of fundamental industrial requirements like erosion protection, anti/de-icing, lightning strike protection and bird strike protection. The integration of these functionalities into a given baseline-design of a morphing structure is a key challenge for the application of such devices in the future. This paper focuses on the design drivers, interdependencies and effects of the integration of the mentioned functionalities into a smart droop nose device.

1 Introduction

Because of the large potential of drag reduction natural laminar flow is one of the challenging aims of the current international aerospace research. For the achievement of the absolutely essential high surface quality, new concepts for the high lift system at the leading edge are required. Besides the well-known Krueger device smart droop nose devices are investigated by various research facilities in Europe [1]-[3]. However, smart droop nose devices at the leading edge are not only advantageous for laminar flow wings. Applied at turbulent wings smart step- and gapless leading edge devices reduce the noise exposure in approach and landing and the drag during take-off [4]. In 2009 the Institute of Composite Structures and Adaptive Systems at the German Aerospace Center (DLR) started a new morphing activity aiming at a smart leading edge device. In national and European projects the concept was consequently advanced. It was tested in structural ground tests [5] as well as in a full-scale low speed wind tunnel test [6]. In the ground test and in the wind tunnel test the feasibility of a load carrying smart droop nose device for a pre-defined aerodynamically optimized shape was successfully demonstrated. Since the work in the recent project was focused on the demonstration of the feasibility of this technology, based on the results of the ground and wind tunnel tests, the integration of required technologies for the application at an aircraft's wing are investigated in the follow-up European project SARISTU (Smart Intelligent Aircraft Structures). This includes namely the integration of

- Anti/de-icing functionality
- Erosion protection
- Impact protection
- Bird strike protection and
- Lightning strike protection.

The participating project partners are all well known for their expertise on the specific tasks. There are the INVENT GmbH for manufacturing of extreme lightweight fiber reinforced structures and prototypes, GKN Aerospace for the de-/anti-icing technology, Airbus Group Innovations for the design of the aeromechanical kinematics and the erosion protection concept, Sonaca as specialist for bird strike protection design and finally VZLU for bird strike tests and a ground test of a full-scale leading edge section.

Especially the effect on the developed design procedure for the design and sizing of smart leading edge devices developed in the previous projects is of interest. Furthermore, the design of a smart droop nose device in SARISTU is focused the first time on the outboard wing due to demonstration and testing activities of a full-scale outboard wing section in a wind tunnel test. The small design space and the large curvature at the leading edge tip of airfoils with small chord length is additionally challenging for the design.

2 Concept and Design Procedure

For the development of the smart droop nose device a structural concept and idea for the realization of the device and a design and sizing procedure is needed. The design procedure must be adapted to the special characteristics of morphing structures for the sizing and optimization of the smart leading structures. A starting point for the structural concept for the realization of the smart leading edge is the patent DE 2907912-A1 [7] (Fig. 1).

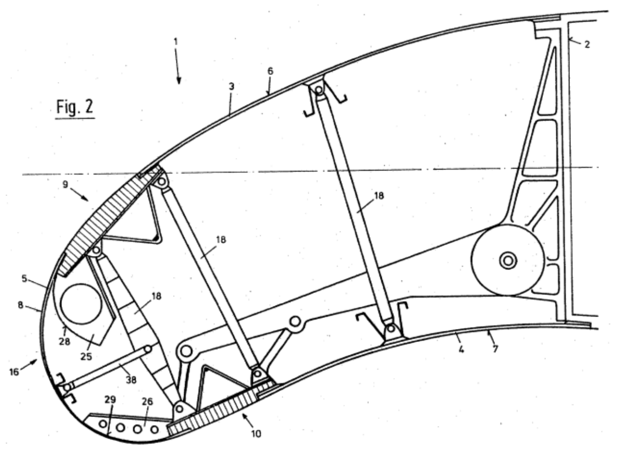

Fig. 1. Dornier patent of a smart droop nose device, 1979, from [7].

It features a completely closed skin without any steps and slots and a comparably simple inner mechanism for actuation of the device. However, the design of the flexible skin is not defined in detail.

For the design and sizing the applied design procedure has to comply with the adverse requirements of morphing structures which are

- Large deformation but at minimum strain
- Stiff enough for high surface quality under aerodynamic loading but low actuator forces for the shape changing
- Load carrying inner kinematic mechanism for high surface quality under aerodynamic loading but low complexity.

2.1 Concept

Based on the patent [7] the developed structural concept (Fig. 2) features a flexible glass fiber structure of the leading edge skin which is actuated by conventional actuators and kinematic mechanisms with several stations in span direction. The glass fiber structure is especially tailored to achieve a desired aerodynamic target shape and fully closed so that there are no steps and gaps and a high quality surface is guaranteed. The actuator forces are introduced into the skin structure by an inner kinematical mechanism which is attached to the skin using span wise oriented omega stringers as load introduction structure. The objective of the design procedure is a GFRP (Glass Fiber reinforced) skin which is tailored for achieving a predefined target shape when actuated at a minimum of load introduction points. To reduce the strain in the GFRP skin when actuated, the design process is based on a certain design philosophy. This philosophy allows only bending of the structure when actuated without considering aerodynamic forces, so that membrane stresses and strains are avoided.

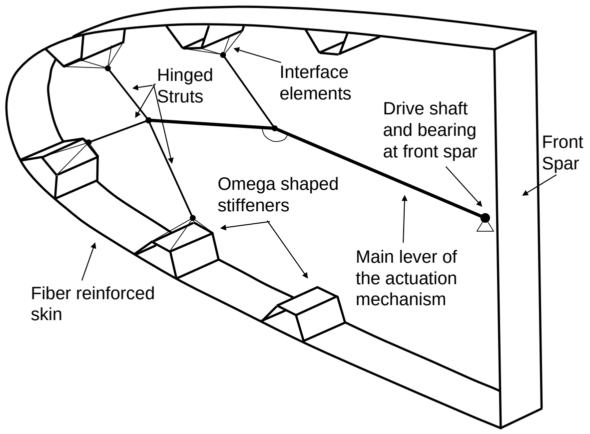

Fig. 2. DLR droop nose concept.

This enlarges the allowable deformation, since the bending strain when deformed is not superimposed by membrane strain. By tailoring of the skins thickness the stiffness distribution and especially bending stiffness is adapted in a way that

- a minimum of load introduction points is needed for actuation of the airfoil
- the stiffness is sufficient to carry the loads in cruise flight and provide a high quality surface
- the target shape can be provided considering the aerodynamic loads in take-off or landing.

However, for the leading edge this design philosophy allows for large deformation of the airfoil since the leading edge represents a continuous geometry. The critical strains are observed at positions of large difference in curvature between un-deformed and deformed shape of the leading edge since the bending strain depends directly on the difference in curvature κ and the thickness t of the skin

$$\varepsilon = \tfrac{1}{2}\,\kappa\, t. \qquad (1)$$

Therefore, flexibility at locations of large difference in curvature between the un-deformed and deformed shape of the structure is provided by tapering the skin to a minimum skin thickness.

2.2 Design Procedure

For the structural design and optimization process a two-step approach is used: Based on the aerodynamic target shape a pre-design phase is started in which the difference in curvature between the un-deformed and the deformed state of the structure is used to estimate a preliminary skin thickness distribution.

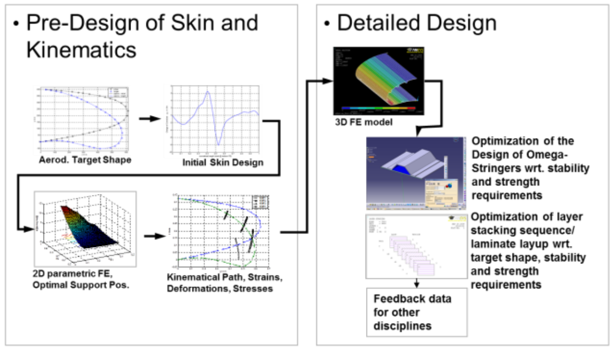

Fig. 3. Sizing and optimization process.

Doing so, the limit strain value for the selected material can be considered in the design so that the pre-design skin is properly proportioned for stress and strain. For limiting the complexity of the inner kinematic mechanism the number of load introduction points i.e. stringers in span direction the process is started with assuming a minimum which means one stringer on the lower panel as load introduction structure for deformation of the airfoil and one on the upper panel for carrying the aerodynamic loads in cruise. In the following iterative design process it may be necessary to increase the number of stringers on upper and lower panel depending on the given surface quality requirements in chord direction.
This structural pre-design is then used as a starting point in the second phase for a detailed optimization process in which a FE shell model of a 2D slice is used for the optimization of the stacking sequence and the position of support position of the kinematics. The results of this 2D optimization are

- the position of kinematical support points needed for an accurate shape during flight

- the trajectories of the interface points when deformed for the design of the inner mechanism
- and the layup and stacking sequence of the skin laminate.

Based on this information a conventional kinematic chain can be designed for this 2D section. Doing this for several cross-sections in span a 3D design can be derived by interpolation. A more detailed description of the design process is given in [8] and [9].

3 Integration of Functionalities

For the application of such a smart leading edge device at real aircrafts several additional requirements must be fulfilled, as they are mentioned in the above section to comply with international certification regulations. It is well-known, that the integration of additional functionalities into a 'baseline' design often leads to penalties in performance and/or weight. Since this is true for conventional i.e. rigid structures it is one of the main objectives of SARISTU to investigate the effects of the integration of the above mentioned functionalities into a flexible and morphing component. In the following section the individual functionalities are presented and characterized with emphasizing the main design drivers and the impact on the other technologies and the overall smart leading edge concept.

3.1 Functionalities

For realizing bird strike protection for leading edges several concepts are known and applied to aircrafts in service. In case of bird strike on a composite wing, the leading edge has to prevent any impact on the composite front spar. After the bird strike the aircraft must be able to continue the flight and to have a safe landing.

In contrary to leading edges made of metal, or Fiber-Metal-Laminates (FML), fiber reinforced leading edges made of glass fibers cannot absorb a bird's impact energy by plastic deformation. One solution to guarantee the bird strike protection functionality of pure GFRP leading edges is therefore a design with a certain thickness of the structure. Unfortunately the above mentioned design philosophy leads to a thin skin at locations with large curvature difference. This is the case in the region of the leading edge tip which is the location with highest probability for bird strike. Bird strike protection for morphing devices with high flexibility can therefore hardly be realized without any energy absorbing sub-structure before the front spar.

The U.S. Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) regulations [10]and [11] allow the usage of alternative solutions with the statement

"[Compliance with this section by provision of redundant structure and protected location of control system elements or protective devices such as splitter plates or energy-absorbing material is acceptable]".

In SARISTU the front spar will therefore be protected by a bird strike protection structure (BSPS).The investigated concepts include bird splitter concepts as well as a hybrid D-Nose concepts which is composed of aluminum sheets and an energy absorbing aluminum honey comb core (Fig. 4).

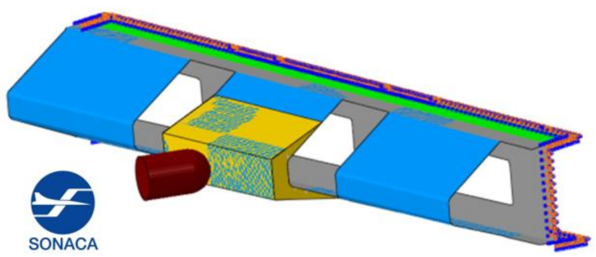

Fig. 4. Simulation of hybrid D-nose bird strike protection structure developed at SONACA.

All other functionalities are intended to be integrated into the leading edge skin laminate. For this purpose a stacking and topology of the various functional layers must be found which guarantees the functionality of each layer and which complies with the manufacturing of the leading edge skin. An example of such a stacking sequence is given in Fig. 5 and discussed in the following sections.

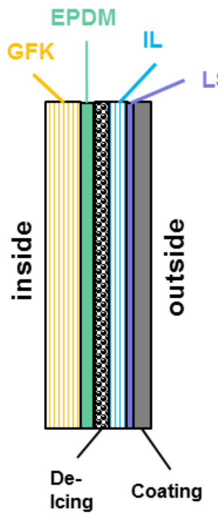

Fig. 5. Sample stacking sequence of functional layers: GFK-Glass Fiber Reinforced Plastics, EPDM – Elastomeric Layer, IL – Insulation Layers, LSP – Lightning strike protection layer or mesh.

An erosion protection is needed on the outer face sheet of the leading edge. Although there are non-metallic erosion protection solutions for leading edges, the performance of metal erosion protection layers in sand and rain erosion tests is outperforming. Considering the need for large deformability i.e. high strains the only metallic material fulfilling both requirements (erosion protection and large limit strains) is titanium. Furthermore, the selection of an erosion protection layer must be considered in combination with a lightning strike protection concept. Since the lightning strike directly impacts the face sheet, the selection of the erosion protection layer significantly influences the lightning strike protection performance. Furthermore insulation layers (IL) are needed between the lightning layers (IL) are needed between the lightning strike protection layer (LSP) and the heater-mat to prevent the lightning strike from affecting the electrical system of the aircraft when breaking into the heater-mat.

Since the basis glass fiber material is a 120°C epoxy material system the application of hot bleed air for anti-icing purpose is not possible. In fact the trend is the application of more and more electric systems on board, so that for the anti/de-icing functionality an electro-thermal heater-mat system like on the 787 is used [12]. An alternative would be the integration of CFRP conductive layers. By variation of the metal sprayed layer thickness the resistance can be adapted to the needs and the laminate can be heated by resistive heating. The heater-mat is integrated with an adhesive film as dry glass cloth into the standard laminate stacking and the manufacturing process.

For protection of the laminate from smaller impacts like for example tool drop an elastomeric layer is useful. The integrated elastomeric layer is intended to be as close to the top face as possible and to absorb the energy for protecting the underlying layers from smaller impacts. For reasons of thermal insulation the elastomeric layer cannot be placed between the heater-mat and the outer face sheet. The functional layers remain therefore unprotected.

3.2 Interdependencies

When integrated in a composite laminate all functional layers have an impact on the shape changing capability of the morphing structure and interact with each other in their functionality. The key design drivers and impact factors on the performance of the morphing leading edge can be grouped into one section which impacts the shape changing capability and one section that impacts the functionality.

First off all, there is a major impact of all applied layers due to the increasing thickness of the laminate. As already mentioned and expressed by equation 1, the bending strain directly depends on the laminates thickness. Since all functional layers have a constant thickness over the circumferential length of the leading edge the strain is increase at constant deflection when compared to the pure GFRP design. Assuming a minimum thickness of about 1mm of the pure GFRP structure, the additional layers add about 0.8mm – 1mm, i.e. about 100% of the nominal thickness with their shares

- Metallic Coating ~0.1mm – 0.2mm,
- LSP/Insulation ~0.25mm– 0.35mm,

- Heater-Mat ~0.23mm,
- Adhesive Film ~0.25mm.

The significantly increased thickness therefore leads to a decreased deformability of the design. Additionally the applied metallic erosion protection shield affects the strain distribution in the laminate. Since the Youngs modulus of titanium is about three times larger than that of the underlying GFRP laminate the neutral fiber of the composite is shifted away from its position in the middle of the laminate. In consequence the strain is concentrated on the inner GFRP layers. This additionally reduces the deformability.

Furthermore the constant thickness of the functional layers along the leading edge chord does have a disadvantageous effect on the bending stiffness distribution: Since the tailoring of the bending stiffness distribution (by thickness tapering) relies on the difference in bending stiffness for achieving a given target shape with minimum actuation points, the application of additional layers of constant thickness decreases the shape accuracy of the design.

Moreover the functionality or applicability of the functional layer itself can be impacted by requirements coming from other functional layers. Already mentioned was the conflict of the protective elastomeric layer and the thermal insulation of the heater-mat. Although a protection of all underlying functional (and pure GFRP) layers would be preferable, the thermal insulation properties of the elastomeric layer results in high temperatures. Calculating the minimum needed heating temperature for a sufficient temperature on the outer face sheet for de-icing the inside temperature of the laminate is above the glass transition temperature of the applied GFRP. An elastomeric impact protection layer can therefore only be integrated for the protection of the pure GFRP layers.

The necessary GFRP insulation layers for the electrical insulation of the heater-mat from lightning strike current again leads to higher temperatures of the heater-mat to reach the required temperature on the outside.

Finally the application of a metallic, high strain capable erosion shield made of titanium is a challenge for the bonding process and the adhesion strength. Especially the fatigue adhesive strength when applied at such a device at large deformations needs special consideration.

4 Optimization of Leading Edge Sections

For the development of a full-span 3D smart droop nose device for the targeted SARISTU wing, geometric target shapes have been generated at the most inboard root and outboard tip position. The 3D design is then derived by interpolation between these positions.

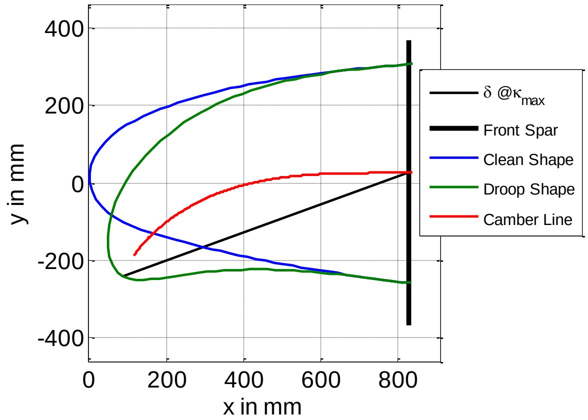

Fig. 6. Target shape at root position for 4618mm chord length.

For both shapes (Fig. 6 and Fig. 7) a droop angle of about 20° and a relative leading edge droop of 3.58% chord are targeted. The length of the neutral fiber of the skin is assumed to be constant.

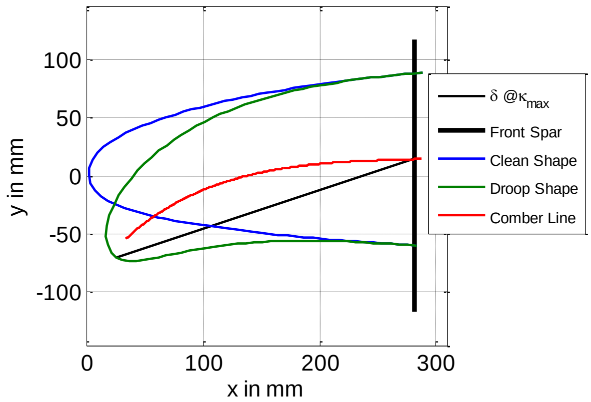

Fig. 7. Target shape at tip position for 1459mm chord length.

Both target shapes are used for the optimization in the above mentioned design process. For comparison the design optimization is performed for a pure GFRP design and subsequently for a design with functional layers as it is given in Fig. 5, but neglecting the elastomeric EPDM layer.

4.1 Shape Accuracy

The results indicate good shape accuracy for both cross-sections for pure GFRP design. The maximum relative deviation of the large inboard cross-section is about 0.20% chord while the deviation of the small outboard section is about 0.23% chord (Fig. 8, Fig. 9).

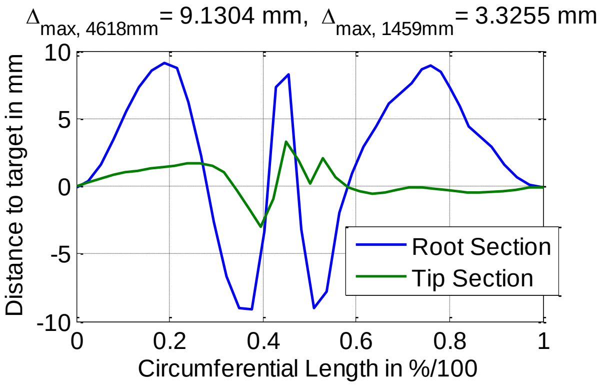

Fig. 8. Distance to target shape for inboard root chord (4618mm) and outboard tip chord (1459mm) cross-section.

Considering the functional layers in the design, the inboard section exhibits a maximum relative deviation of about 0.33% chord and the outboard section of about 0.35% chord.

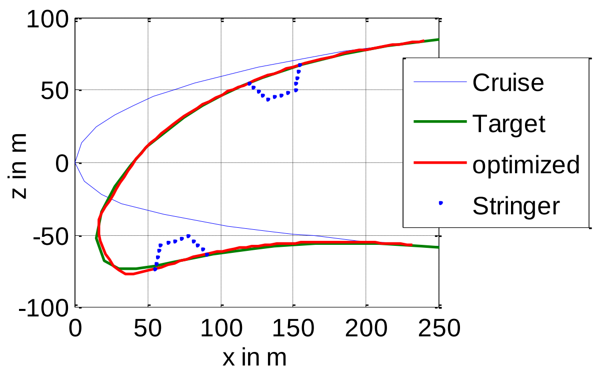

Fig. 9. Shapes for pure GFRP design at tip position for 1459mm chord length with a distance to target shape of 3.3mm.

Although the relative deviation is small for both cross-sections it becomes clear, that the achievable shape for pure GFRP design at the outboard section will not fulfill the aerodynamic requirement of a smooth shape change. The main difference between the achievable shapes for the small and the large cross-section is the distribution of curvature. Having a closer look at the curvature of the optimized droop shape in Fig. 9 an inflection point can be noticed at the tip of the leading edge at about 45% circumferential length of the airfoil (Fig. 10).

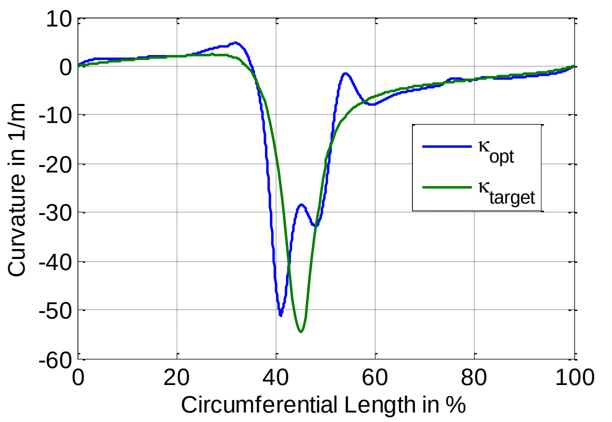

Fig. 10. Curvature distribution of optimized drooped shape at tip position for 1459mm chord length of pure GFRP design.

For an effective aerodynamic shape the curvature along the profiles upper surface plays a major role since it triggers directly the sensitive pressure distribution of the airfoil. To achieve an optimal generation of lift, the curvature distribution must be monotonically decreasing from the point of largest curvature at the stagnation point (i.e. the leading edge tip). An inflection point in the curvature distribution is undesired and possibly triggers a sudden, increase in pressure which may result in a less effective suction peak or flow separation.

The reason for this effect is the addition of layers with constant thickness. In consequence the location with the largest curvature in un-deformed position, i.e. the leading edge tip, cannot be straightened properly when drooping into the target shape. To overcome this effect a very detailed design of the stiffness distribution at this location is needed. Since the applied pre-preg material triggers additionally a discrete thickness tapering with steps of 0.125mm or

0.25mm, the same effect can be observed for reasons of manufacturing requirements. For example there are a minimum tapering length for the manufacturing and the requirement for a balanced laminate, i.e. drop-off layers must be considered to be symmetrically. These boundary conditions lead to a limited space in the design of the stiffness distribution and this undesired effect on the resulting curvature distribution which is even worse in the design with integrated functional layers.

4.2 Strength Assessment

Besides the assessment of the airfoil shape and curvature for the aerodynamic effectiveness the assessment of the structural strength is mandatory. The strength assessment is based on the measured limit strains for the applied GFRP material [9]. Due to the large cross-section at the inboard position of the wing the change in curvature when deformed is moderate compared to the outboard sections. The most critical position and strain is the bending strain in circumferential direction of the airfoil. For the pure GFRP design the maximum strain in the large cross-section is about 0.53% at the lower panel of the leading edge. At this location the load is introduced into the structure and a sudden change in stiffness is located at the position were the stringer foot is attached to the skin (Fig. 11).

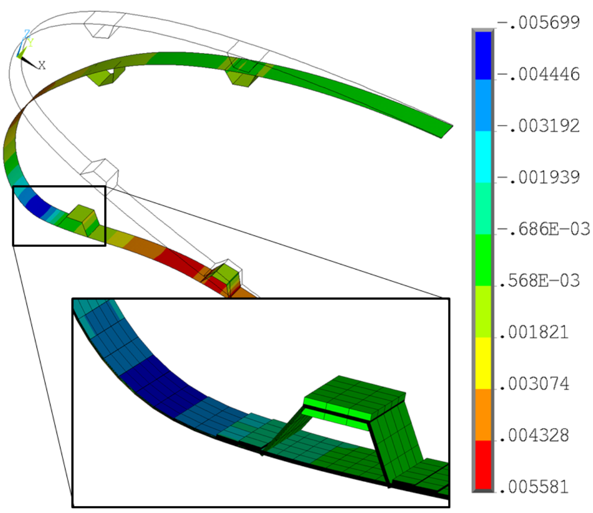

Fig. 11. Strain distribution of the inboard cross-section in circumferential direction with a maximum strain of about ±0.56% in pure GFRP design.

Applying the titanium erosion shield, heater-mat and isolation layers leads to slightly increased strain on the inner layers of the airfoil due to the shift of the neutral fiber due to the high stiffness titanium as face sheet and the additional thickness. The maximum strain on the inside of the airfoil in this case is about -0.76% while the outside strain is about 0.62% (Fig. 11, Fig. 12).

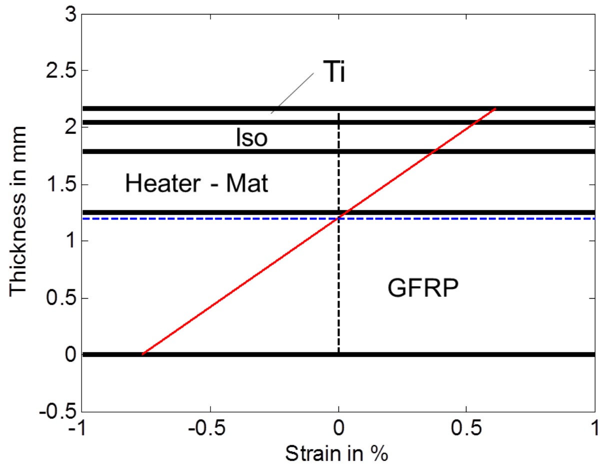

Fig. 12. Neutral fiber of the laminate with integrated functional layers (blue) of the inboard cross-section. Strain (red) assuming a linear through the thickness distribution.

Due to the much larger difference in curvature between the un-deformed shape and the target shape, the strains at the outboard section are much larger, too (Fig. 13).

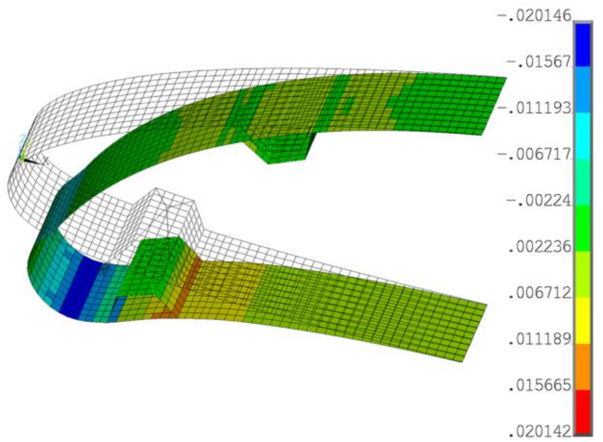

Fig. 13. Strain distribution of the outboard cross-section in circumferential direction with a maximum strain of about ±2.0% in pure GFRP design.

The maximum strain in circumferential direction is found to be about 2.0% which is nearly the absolute limit strain for a pure UD design with exclusively 0°-fibers. Additionally the application of the heater-mat, isolation layers and a metallic erosion shield foil increases the critical strain on the inside of the airfoil even more. In this case the maximum strain is found to be +3.6% on the outside layer and about -4% on the inside layer.

5 Experimental Tests

For validation of applied finite element models and investigation of the effects of a titanium erosion shield applied at a basis GFRP laminate experimental tests are performed. Since the design philosophy allows only for bending deformation of the smart leading edge structure the four point bending test DIN EN ISO 14125 [13] represents an ideal test method for validation and verification. The configuration of the 4-point test-rig depends on the material class. Thus, GFRP samples with thickness of 2±0.1mm are tested and a span length L of 75mm is required with 25mm span length of the stamp. The tests are carried out in two tensile testing machines (1484 and 1476, Zwick GmbH & Co. KG) with a 5kN load cell (Zwick GmbH & Co. KG). The deflection sensor is positioned in the middle of the span (W10TK, Hottinger Baldwin Messtechnik GmbH). The tests are conducted with a velocity of 2mm/min and a pre-stress of 3N. The radius of the load mountings is 2mm respectively. A specimen after static test with applied strain sensor is presented in Fig. 14.

Fig. 14. Specimen, four point bending tests with GFRP 2.0mm basis laminate and 0.4mm titanium erosion shield after static test.

For comparison and validation the four point bending test is modelled using composite shell elements SHELL181 of the ANSYS element library. The simulation is performed considering geometric non-linear behavior including contact between the bearing and the specimen and the load bearing and the specimen. In Fig. 15 a superposition of a test of a UD (0°)-specimen and the corresponding FE analysis with the bending strain in x-direction is presented. Accordingly the force-displacement curves are given in Fig. 16.

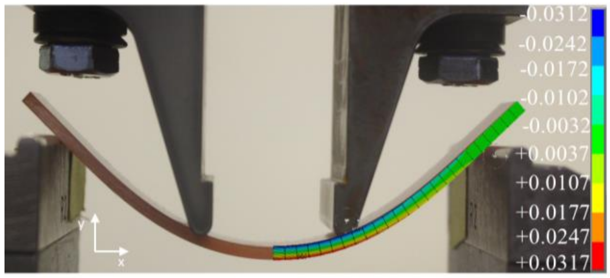

Fig. 15. Superposition of experimental four point bending test and FE simulation of pure 0°-GFRP material with a maximum strain of about 3.17%.

The results of the simulations agree in a wide range of the displacement with the results from experimental tests. Due to the high flexibility of the material, the reference specimen (pure GFRP, 0°) could not be tested until failure.

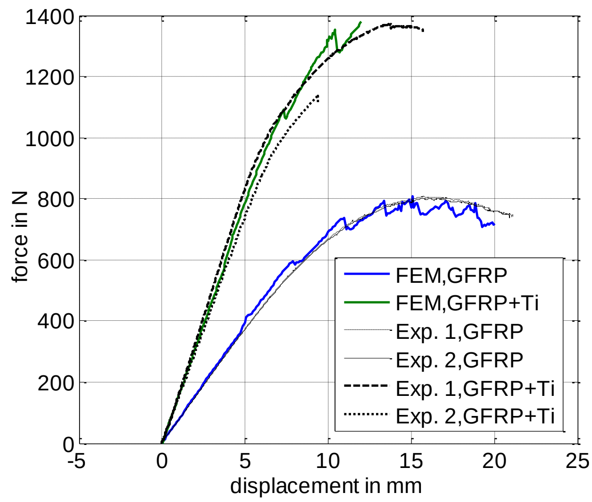

Fig. 16. Comparison of experimental results and simulations of four point bending tests with GFRP 2.0mm basis laminate (blue) and 0.4mm titanium erosion shield (green).

The non-linear behavior observed is the result of a bit by bit slip-through of specimen between the bearings.
In contrary the specimen with the 0.4mm titanium foil applied exhibits a non-linear behavior which results from fiber breakage and collapse on the inner side of the specimen as depicted in Fig. 14 (upper). Due to the shifting of the neutral fiber, the strain is concentrated on the inside of the structure which leads to matrix/fiber failure at the position of the loading pins. This characteristic failure mechanism was similarly captured by the FE simulations with applying the Puck failure criterion (Fig. 17).

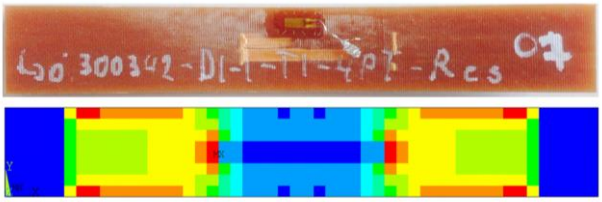

Fig. 17. Comparison of experimental failure location and Puck failure criteria of four point bending tests with GFRP 2.0mm basis laminate and 0.4mm titanium erosion shield.

Additionally to this test further tests are currently being performed addressing the integration of additional functional layers and the fatigue behavior under cyclic loading. For assessment of the adhesive strength of the applied titanium foil roller peel tests are performed.

6 Conclusion

The development of smart, morphing structures for high quality surfaces in aerospace applications is a challenge. The integration of industrial requirements like erosion protection, anti-icing, bird strike protection and lightning strike protection without affecting the morphing performance increases the challenge even more. In the European project SARISTU solutions for the integration of the mentioned functionalities into a smart leading edge device are developed. The integration needs careful design to not jeopardize the performance of such kind of high-lift devices.

The paper focuses on the integration of functional layers into the leading edge skin considering their interdependencies in the design. Not only the additional thickness which results from the integration of additional functional layers is a challenge for a proper design for stress and strain but also the combination of the functionalities itself. The electric insulation of the anti-icing system for lightning strike protection for example affects adversely the effectiveness of the heating system. Furthermore the adhesion strength of metallic erosion protection concepts on morphing FRP components plays a major role.
The first design of a smart droop nose device for an outboard wing section in SARISTU reveals an even larger challenge for the integration of the functionalities in leading edges of slim airfoils as well as for the design of the kinematic mechanism for actuation. Although the design is feasible for inboard wing sections, the strength and limited design space at outboard wing sections is critical. However the discrete thickness of prepreg material and manufacturing requirements set a natural limit for the tailoring of the composite so that given target shapes are no longer achieved in acceptable tolerance limits. For the application on outboard wing sections new innovative skin materials will have to be considered in future works.

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