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From development of multi-material skins to morphing flight hardware production

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The INVENT GmbH rises in the EU project CHANGE under the lead of Tekever and in cooperation with project partners to the challenge to manufacture a gapless and flexible solution for morphing leading and trailing edges of small unmanned aircrafts. Several pretests with thought-provoking material combinations are evaluated previous to the design phase. Solutions for load introduction structures for highly flexible skins for aerodynamic applications are proposed. In parallel to the material design process INVENT produces and tests fibre composites with elastomeric material matrices. As a result a composite with carbon fibre properties parallel to the fibres and elastomer properties perpendicular to the fibres is being developed. Following the production, this material can be combined with epoxy-prepreg in co-curing cycles, an essential demand for both stiff and flexible wing structures. Apart from this, two concepts with conventional fibre composites and two with advanced elastomeric material concepts are designed by the partners Deutsches Zentrum für Luft- und Raumfahrt, Middle Eastern Technical University and Technical University of Delft. Based on calculations conducted with finite elements and CAD-designs by the partners prototypes are built and prepared for a half span wind tunnel test preceding the flight test. In cooperation with the partners a trade-off between structural strength as designed, expected morphing performance and manufacturability has been assessed. Deduced from the wind tunnel test one configuration for the flight test will be chosen. INVENT is in charge of manufacturing the fitted morphing leading and trailing edges for the flight test. In parallel with the preparations of the flight test a skin material test campaign will be conducted at INVENT. The target of the test campaign is a qualitative evaluation of the morphing skin performance regarding cyclic loading and exposure to environmental influences. The influence of defects (manufacturing defects and impacts) on the degradation of the skin material will be tested in specially designed test stands. An auxiliary wing structure will be used to create a realistic surrounding. Amongst others ultrasonic inspection will be used to evaluate the progression of defects in the skin.

I. Introduction

THE current efforts of most scientific research activities in the field of aerospace vehicles is the optimization of performance regarding energy consumption and thus aerodynamic shape. The project consortium of CHANGE has engaged in optimizing the wing and profile shape of a small unmanned aircraft. The main role of INVENT in the project is the setup of a material database, the provision of advice regarding manufacturability, the development of a

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morphing skin and the manufacturing and ground testing of the morphing elements based on the designs by the respective partners. Since several different approaches are made by the project partners and a rather wide variety of morphing materials for different load scenarios are proposed they are tested in preliminary test scenarios by INVENT.

Amongst the combined materials an in-house elastomer/carbon fibre prepreg with a ply thickness of 0,19mm for the co-curing with standard epoxy resin prepreg has been designed and proposed. After the proposal of a range of promising material combinations for morphing scenarios, several material tests for calculations were made to allow qualitative predictions on the material and the designed morphing element. The information gained in these tests is then used by the partners to finalize the design of two leading edge and two trailing edge elements in close collaboration with INVENT regarding the manufacturability. The span extension of the CHANGE wing, designed by Universidade da Beira Interior (Gamboa & Santos, 2015), was however not build by INVENT -. These prototypes are used to validate the calculations made by ARA in a wind tunnel test campaign using a half span model of the wing with a “plug & play” interface for a quicker exchange of the morphing elements. Following the wind tunnel tests only small modifications were made to the skin and surround structure designs to allow the manufacturing of two sets each for the flight model.

In parallel to the wind tunnel test campaign INVENT engaged a ground test campaign to assess the behaviour of the material combinations of the morphing element designs regarding degradation due to cyclic loading and environmental impacts such as exposure to UV radiation and high operating temperatures. For this test campaign a test stand housing a half span wing box substitute was designed and built.

II. Materials And Compliance

A. Materials and Compliance Matrix

As part of the actions in the course of CHANGE the creation of a materials and compliance matrix was a milestone. This matrix is organized as an MS Excel spread sheet with detailed information on the envisaged materials to be used throughout the project. Table 1 provides an overview of the information that was gathered in the matrix. It is attached to a report describing how to work with the material data collection and how to evaluate the best options depending on the linked production process. Suitable materials for the morphing wing structure as well as actuators were listed.

The materials proposed by the contributing partners were listed in the worksheet “Material collection”. Relevance for morphing as well as linked process is listed as the main focus. The availability of the material itself would be assured by heritage and reference. Data sheets, either based on manufactures TDS or material properties data from the project partners, were collected and linked in the Excel file. The decision for the morphing technologies to be applied as well as the design freezes for subsequent manufacturing were founded on that data base as a consortium decision. The recent status, the basis to start the design and skin development actions was documented throughout the project. Therefore this material and actuator collection can be considered as not completely finished and as a living document throughout the definition phase of the project whenever refining the morphing technologies to be applied and assessed.

Columns	Information
Material type	Type of material
Material Designation	Product name
Linked Process	How to process, special procedures
Properties assisting Morphing	Morphing assistance – a short description
Heritage / References /Availability	Reference – preliminary use?
Available Data Sheets	Available engineering constants
Properties evaluation by Tests needed in	Which additional data has to be obtained for simulation?
CHANGE Project Partner Company / Name	Who to contact when questions arise?
Illustrating Picture	Usage in specific concept or design? / General usage?
Notes	Useful comments / information adding to the points above.

Table 1: Content of the "Materials and Compliance Matrix"

The Excel file contains also separate material data sheets to give more details as the summarization and overview of the worksheet “Material collection”. These can serve the designer of a morphing wing element as a handbook on suitable materials. Material properties as well as the application of the material within the wing are named by the data sheets.

B. Commercially available Prepregs

Some of the commercially available fibre composite materials show comparably high strain rates. Especially toughened glass fibre prepregs show high potential for moderate to high bending loads. Since they are well obtainable and low-priced (compared to in-house elastomer prepregs) they are favourable for moderate to high bending loads. Material data is adequately tested and material parameters are available from the manufacturers (Gurit EHG250 (Gurit GmbH, 2007)) or existing at the project partners (HexPly®913-Prepreg (Hexcel Corporation, 2007)).

C. Elastomeric Prepreg – “ePreg”

The basic idea of the designed ePreg is the combining of the high tensile strength of the carbon fibre and the high ductility of the elastomeric matrix. Combining these two outstanding characteristics for the use in one material promised almost ideal conditions for a material for morphing applications. Fibre composites are predestinated to realize the joining of two materials with different characteristics.

The properties of the elastomeric materials are highly adjustable and thus customizable to most application scenarios. A vulcanizing agent for example can be used to influence the temperature stability. The used EPDM shows a temperature stability of approx. 100°C; however it is also cold-resistant down to -50°C. Due to the saturated polymer backbone, the used EPDM material has a chemical resistance to many polar solvents, such as alcohols, esters and ketones. It is resistant to salt solutions and oxidizing media. In addition to resistance to some hydraulic fluids and silicone oils it is highly UV and weather resistant.

In addition, the material is designed with a mixture of various additives to allow the co-curing and vulcanization under process parameters of epoxy resin systems. The composition of the mixture may contain up to twenty additives. The often empirical experience of the recipes belong to the "manufacturer's know –how”. The EPDM compound used was not, such as in car tires, vulcanized in a closed mould but with the epoxy prepreg in an open mould. Through the autoclave pressure of 5 bars and the temperature increase to 125°C the vulcanization process was completed after only 3-7 minutes. A longer curing cycle governed by the commercial prepreg has no influence on the subsequent material behaviour.

The carbon fibres used for the material tests were of the type *PYROFILTM TR50S15K* manufactured by GRAFIL INC (Grafil Inc., 2010). The fibres are arranged to an unidirectional dry tape with a layer thickness of 0.075 mm. The low layer thickness and the unidirectional fibre layup were key reasons for choosing this material. The filaments have a diameter of 0.007 mm, and 153 filaments are combined to form one roving. The starting material for the nest production has a fineness of 1000 tex and a fibre density of 1.82 g/cm3. The fibre layer consists of two layers with a base weight of 38 g/m2. The roving layers are connected with a resin in order to increase the

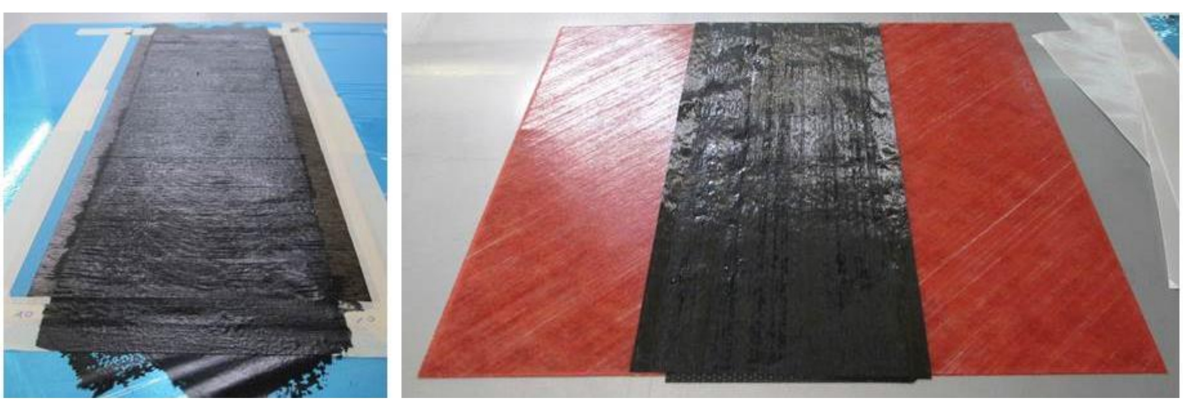


Figure 1: Manufacturing and integration of ePreg tensile specimen

shear strength for the processing of the resulting 80 g/m^2-layer. According to the manufacturer, the proportion of this resin was 6 ± 4 %. GRAFIL INC. indicates the tensile strength of the fibres with 4900 MPa and the tensile-modulus with 240 GPa.

D. Test scenarios for composites with elastomeric matrices

In order to evaluate the properties of the developed ePreg material several tests were designed to allow a transfer for the use as adapted engineering constants for the design activities of the partners.

The material behaviour under tensile stress often has a major influence on the choice of a material. In fibre-reinforced composites with elastic matrix the behaviour under tensile loading is even more influenced by the loading direction, than it is in conventional fibre-matrix systems. In order to compare the results a new specimen geometry was designed by deriving it from typical specimen geometries for fibre composite materials.

These new specimen designs are possible starting points for a standardized comparison of different elastic matrix systems, but by no means should it serve as a fixed template.

The sample geometry used is based on the DIN EN ISO 527-4 type 2, but has no tabs for force transmission or centering. Only the total length of 250mm and width of 25mm are adopted. No strain gauge is provided, as even foil strain gauges usually only endure 5% elongation and are expected to be damaged by the shock wave of the fibre. Furthermore glued DMS influence the behaviour of near-surface elastomer layer and therefore do not depict the material behaviour in the neutral layer.

Figure 4 shows a sketch of the tested specimen and the dimensions derived from the DIN EN ISO 527-4 type 2 specimens. To allow a bending perpendicular to the pulling direction, a test area of 100mm * 25mm is chosen. Smaller widths hinder this bending caused by minimal sample asymmetry and lateral contraction effect. This is caused by a supporting effect of the solid sample parts. The total length of 250mm was adopted as these are the usual sample geometries, along with the width b1. The thickness h is taken only slightly reduced as default.

For the specimen described in this section, a single layer ePreg and one enveloping layer EPDM without carbon fibres on the top and bottom. These protective layers are necessary, since a single layer of the prepreg is too fragile to be loaded individually. Exemplary results of the tests of 0°- and 90°-fibre orientation specimen are shown in Figure 2 and Figure 3.

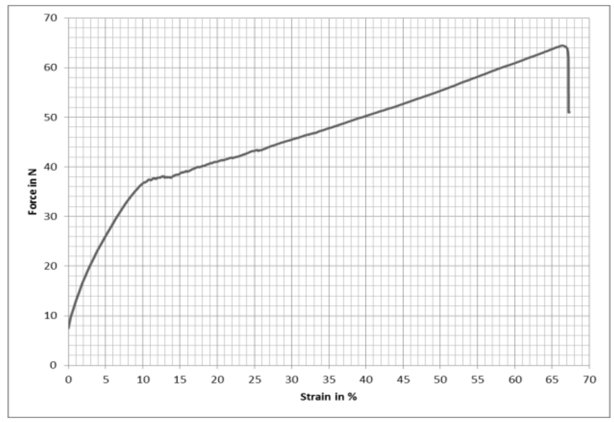


Figure 2: Non-linear, matrix dominated behaviour of 90°-ePreg layer

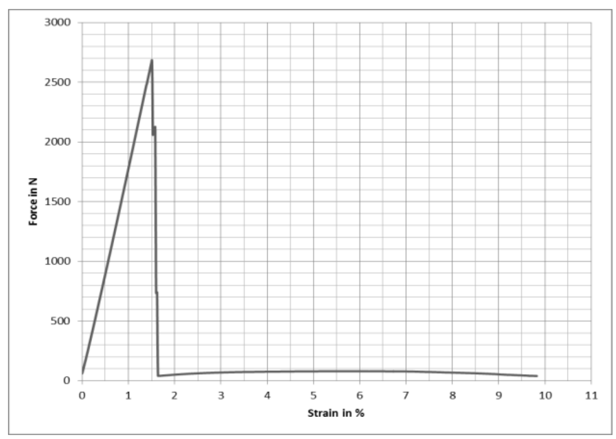
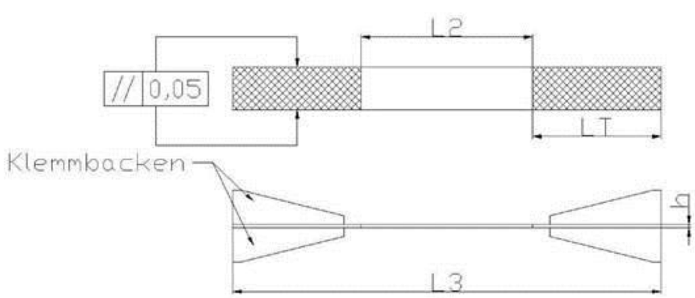


Figure 3: Linear, fiber dominated behaviour of 0°-ePreg layer



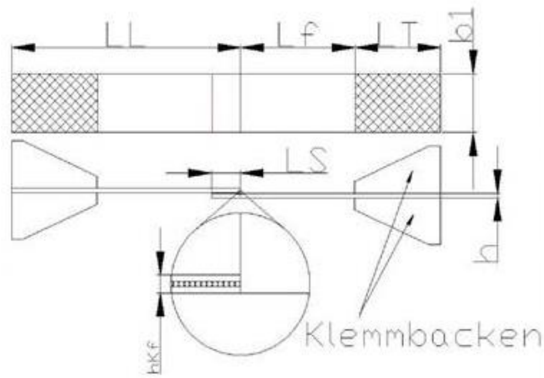
Abmessungen des Probekörpers		eFVW (mm)
Gesamtlänge	L_3	≥ 250
Dicke	h	$1 \geq h \geq 10$
Breite	b_1	$25 \pm 0{,}5$
Abstand zw. den Krafteinleitungen	L_2	$100 \pm 0{,}5(1)$
Anfangsabstand zw. den Klemmen	L	≥ 120
Länge der Krafteinleitungselemente	L_T	≥ 75
Dicke Krafteinleitungselemente	h_T	$=h$
Messlänge (für Längenmesseinrichtung)	L_0	$t.b.d.$
Durchmesser der Zentrierlöcher	D	$t.b.d.$

Figure 4: Proposed and applied dimensions for the tensile testing of ePreg specimen

Single-Lap-Shear Tests

Figure 5 shows a sketch of the SLS-specimens that were used to characterize the connection between a thermo set epoxy based resin and the elastomeric synthetic rubber resin. The target was to describe the failure mode of this kind of connection. The test is derived from the DIN EN 1465 and modified to suit the material variations. The test is intended to produce data for the determination of the tensile shear strength of lap joints between high-strength metals and plastics. However, in the use of elastic matrices, such as in CHANGE, it was used to determine the weak link in the composite. By using a prepreg as an adhesive film in this sample configuration, various properties were determined qualitatively and quantitatively. This approach was useful because a SLS bond was to be used by the partners for the design of connections of the skin to the solid wing box.

Geometrically, these specimens do not differ from the standard specimen. Only the thickness of the bonding layer of ePreg and EPDM and their properties differ. ePreg, EPDM and prepreg are processed in the same autoclave



Abmessungen des Probekörpers		eFVW (mm)
Gesamtlänge	$---$	$\geq 187{,}5$
Dicke des festen Fügeteils	h	$2 \pm 0{,}1$
Breite	b_1	$25 \pm 0{,}2$
Länge der festen Fügeteile	L_L	≥ 100
Freie Länge	L_f	≥ 50
Überlappungslänge	L_S	$12{,}5 \pm 0{,}1$
Spannlänge	L_T	≥ 30
Dicke der Klebefuge	h_{Kf}	$\leq 0{,}5$

Figure 5: Proposed and applied dimensions for the single lap shear testing of ePreg specimen

cycle. It was expected that due to the different thicknesses of EPDM and ePreg, the influence of deflection would vary greatly. The eccentric bending (due to the specimen asymmetry) lead to a peeling effect at the ends of the joining surfaces. The reason for the failure therefore was a stress peak at the ends of the lap. The average shear stress was in this case not the actual local stress. The shear force is not distributed evenly over the surface. Especially when comparing the values reached by the EPDM with those of the ePreg the bond line thickness played a crucial role. The specimens failed by a scribe in one of the overlapping ends. The samples in which the adhesive layer was made of pure elastomer also failed due to this effect. The stress peak at the edges created a scribe line in the region between EPDM and fibres. The crack is initiated at a joint part and runs through the middle of the overlap where it penetrated the EPDM layer. It was found that the ultimate load of the connection is less than that of pure EPDM. The almost tensile loaded elastomer layer fails at higher loads. This behaviour describes the interruption of the monotonic decay of the curve in Force-Strain-Diagram, thus creating the need to improve th fibre/matrix interface.

3-PT-Bending Tests

For the 3-pt-bending test, the DIN EN ISO 14125 A Class III was used as the starting point. The dimensions of 100mm x 15mm samples were of the same size as the ones used in the standard. Only the sample thickness was decreased by the 8-ply quasi-isotropic construction to approximately 1.79 mm.

With the bending test, a very important property for elastic fibre composites was investigated. It has a great importance, since it was expected that components of elastic composites can tolerate much larger deformation before fatal failure. Assuming that the outer fibre layer is flush with the surface, fibre fracture can be assumed to be the dimensioning factor at the break elongation of the fibre. In case of large deflections the DIN EN ISO 14125 A Class III uses a corrected equation for the strain, which was used.

Figure 6 shows the compression and tension failures of the 3-pt-bending specimen. The behaviour of the bending specimen made of ePreg is similar to the behaviour of conventional composites. The isotropic stacking sequence ensures a very fibre reliant result.

The first visible failure mode is the buckling and delamination on the compressed side of the specimen. The laminate failure occurs at the fibre/resin interface resulting in a sublaminate buckling of the innermost layers. Figure 6(l) shows the end of the test when the buckling was clearly visible.

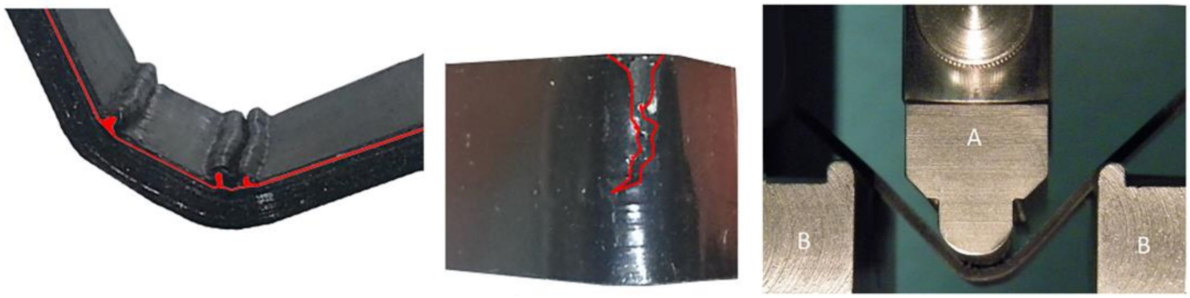


Figure 6: Failure of 3-PT-Bending specimen (single ply delamination (l.), tensile failure (c.)) and the test set-up (r.)

The second failure occurred only in one specimen, which was tested with the fastest speed. A scribe expanded over the tensile loaded side of the 3-pt-specimen. Further inspections are necessary to unveil the speed/strain correlation. However it is very likely that a linkage between the test speed and the failure mode can be found.

Fibre-Bundle Pull-Out Tests

The interface of elastic composites seems to be the weakest link in this material set up due to the abrupt stiffness change. In order to assess the weakest link in the material combination this test was adapted and carried out. Figure 7(l) shows a sketch of the specimens used to investigate the interface strength of fibres and matrix.

The failure of the fibre layer occurred prior to failure of the fibre-matrix adhesion. However, the fibre ends were clamped and load was possibly introduced into the fibres. Cracks caused by the milling during preparation and at the transition to epoxy prepreg fibres were possibly weakened. With the experience gained, the following adjustments are proposed.

The test specimens were clamped in the outermost area of the tab strips so that the fibre layer was not fixed in the region of the test surface. It has been shown that only the adjustment of the clamping is insufficient. For future specimens the fibre layer should lie far outside the clamped area. The fibres may not be held by the jaws as in the test performed. Furthermore, the fibres should be as free as possible in the test area. It is advisable to omit the laminate structure in the area of the test surface. However, the fibrous sheet must be supported to be not damaged by the autoclave pressure or the used tooling. The support can be above and below the fibre layer. This could be realized, for example by a silicon strip below the carbon- fibre fabric. If it can be ensured that the fibres are not damaged in the production process, then this variation is preferred. However, there is a risk that resin from the cap strips rises into the dry layer. The impact of this effect can vary depending on the combination of materials.

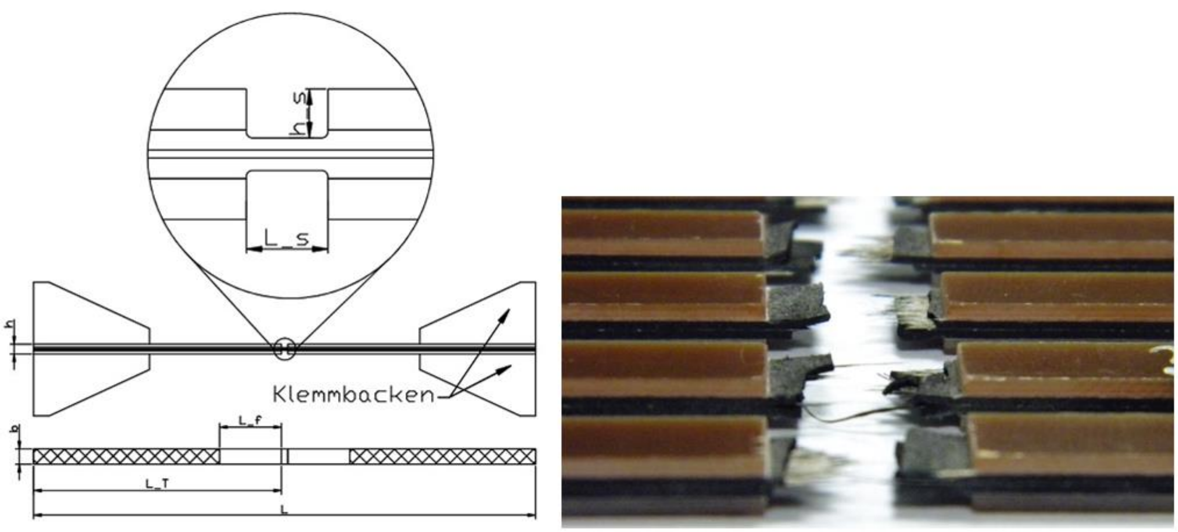


Figure 7: Geometry of Fiber-Bundle-Pull-Out specimen (l.) and the failure (r.)

The manufacturing of the specimen also allowed examining a way to mill the produced composite to a certain degree. The following parameters have shown good results:

- High cutting speeds (~60 m/min)
- Small steps in the depth of cut (~0,1mm)
- Highly positive tools (α=12°, γ=25°, radius of cutter < 10 µm)
- Cooling of the material below -10°C

Wrinkling/ Shear Frame

The behaviour of the wing skin under torsion load shows a critical aspect for the use of wing skins made from elastic composites and other adaptable materials. The ideal material for the demanded application is a material that can easily be deformed by the actuators; however it should provide sufficient stiffness to be loaded by the air stream and aerodynamic forces. Elastic composites offer, through their high anisotropy, the possibility to fulfil these requirements. Nevertheless, elastic fibre materials are very susceptible for the shear forces appearing with the wing twists.

Figure 8 shows the shear frame which allowed a first qualitative investigation of the material behaviour selected for CHANGE. Moreover, Figure 8 shows the dimensions of the skin specimens. The skin specimens were cut with a stencil after vulcanizing. The holes were punched out with a hammering tool. As a stencil a silicone sheet was used. With the silicone stencil the specimen can be adjusted very well. Nevertheless, for further specimen a metal sheet is to be used to ensure a better accuarcy with the cutting. The constructed shear frame uses a threaded pole with a M10 fine-pitch thread. A rotation thereby corresponds to a feed of a millimetre. To stretch diagonals about 1%, it requires 2.47 handle turns (U). According to this, 12.35U for 5% and 24.7U for 10% applies. According to the edges of the nuts, 1/6 steps were used to set the frame and therewith the skin geometry.

By using a turned coordinate system which corresponds to the original coordinate system turned by 45° it was possible to allow compressive bulging to the skin element. Instead of x, y the diagonal coordinates x”, y” were used. x” represents the tensile direction and y” the compressive direction; with the x”-axis being the axis of the threaded pole. For a qualitative description of the material behaviour it is important to know that the plate stiffnesses B_x, B_y, $B_{x,y}$ respectively $B_{x''}$, $B_{y''}$, $B_{x'',y''}$ and the type of clamping have a major effect on the behaviour of the loaded specimen.

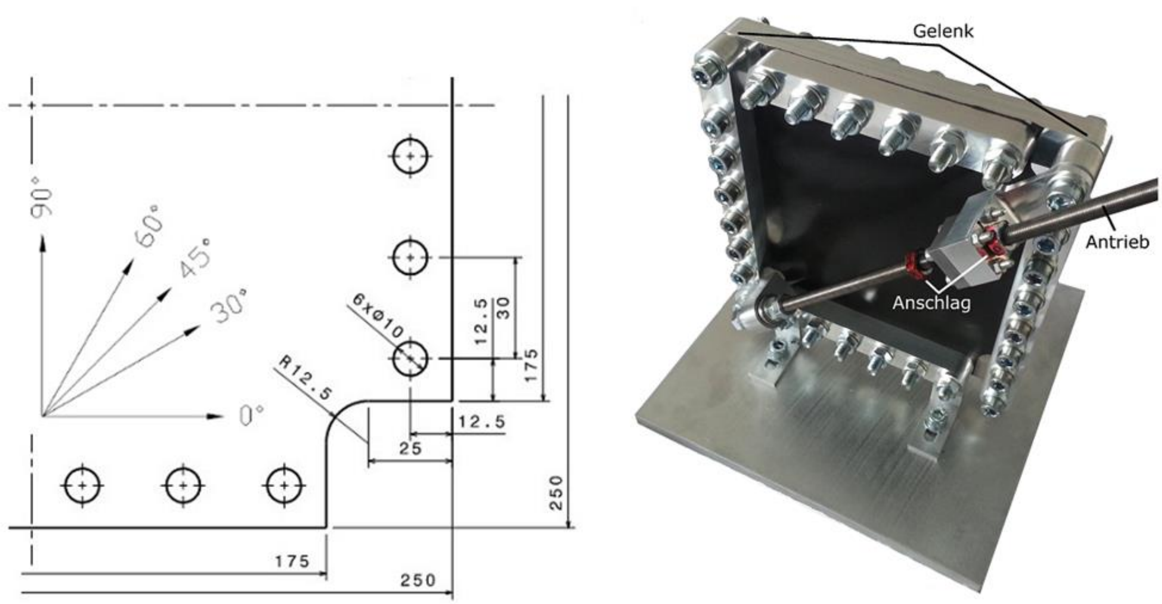


Figure 8: Elastic skin specimen geometry (l.) and shear frame (r.) for the evaluation of elastic skin behaviour under shear load

In the tensile direction x” the behaviour was seen be uncritical regarding wrinkling but in the y”–direction the behaviour of the skin with compressive loading would result in wrinkling/buckling. The tests were performed creating no plastic deformations in the elastic skin or fibre failure in the ePreg layer.

Figure 9 shows differently orientated skin specimens and their response to the shear loads imposed by the frame. The number of wrinkles is an acceptable indicator for the description of the shear buckling stiffness since these first tests have a qualitative objective. A high amount of wrinkles in the direction of the y” indicate a weak stiffness for the chosen fibre orientation. Maximums and minimums appear as light and dark areas and in this way allow the determination of the wrinkling behaviour.

Figure 9 shows that the fibre orientation has an impact on the wrinkles and their deflection. The fibre orientation (in this case 135°) in compression direction results in high plate stiffness B_y and therefore lowers the number of wrinkles. As expected the x”-direction showed no wrinkles.

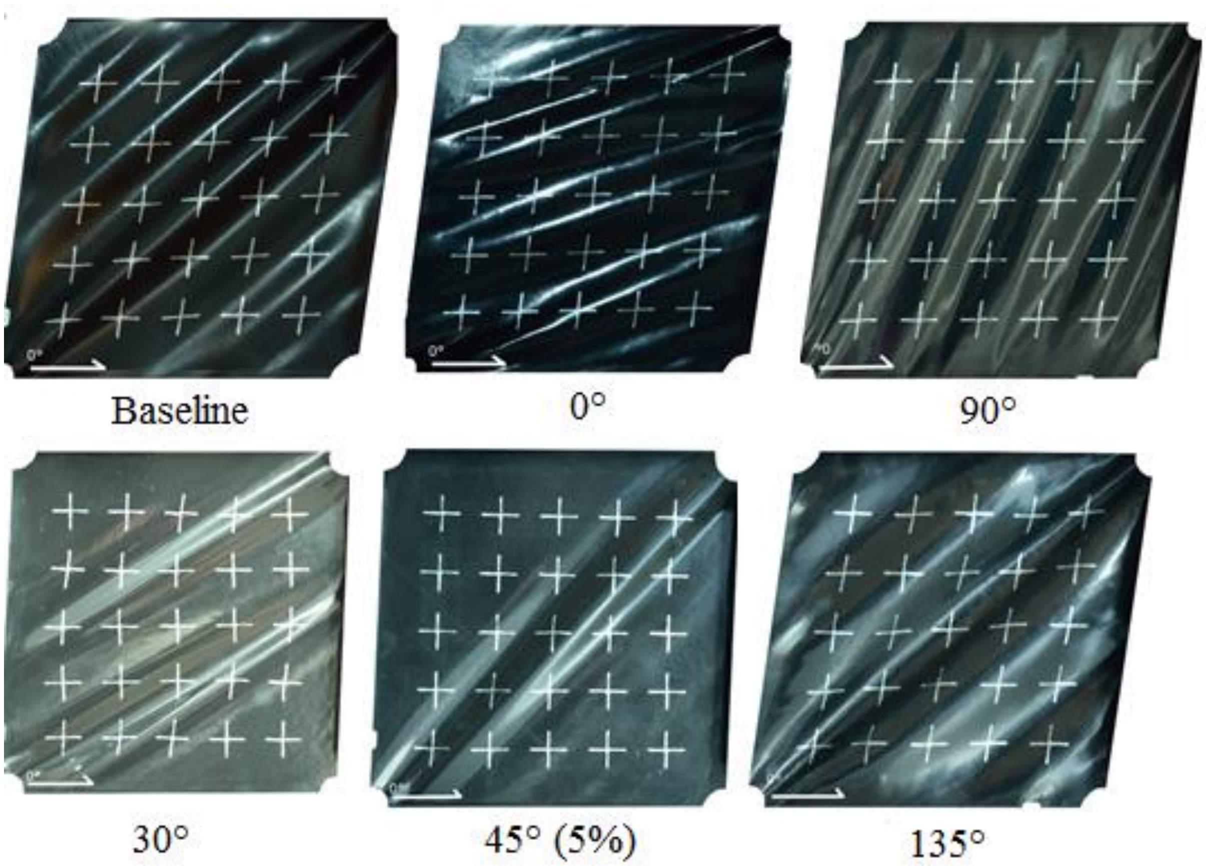


Figure 9: A choice of skin specimen with different fiber orientations at 10% diagonal strain

III. Skin materials for the morphing wing

INVENTs main objectives were the material specimen preparation with material mixes that were based on the feedback from the design groups and on the INVENT experience for morphing applications. Different elastic matrices with promising properties - that means high strain rates and material processability with industrialized processes- were investigated. Material samples of elastomers were acquired and tested in terms of preselecting them for the project partners with focus on processability. This included the employment of novel and promising material mixes.

In order to be able to assess their processability, manufacturing trials were performed and evaluated. Specimen based material tests to evaluate the behaviour of the chosen material and manufacturing trials to adapt the production process were conducted. The preparation of the test panels was based on the development of the manufacturing process for elastomeric matrices with fibre reinforcement. To evaluate basic material properties static tests were performed on specimen using a 20kN Zwick. These coupons were derived from the material combinations. A basic material made from reinforced elastomer which suits the needs of the different morphing concepts was designed and has been individually fitted for the application in the designs of the project partners.

IV. Approach for the material design

The different morphing concepts result into very specific needs to the wing skin properties. Starting with only the expected loads and strains basic material designs were composed. These concepts cannot be combined in one material configuration as the directions of deformations are perpendicular to each other or the concept would need a stiff wing cover or an elastic one. The different skin solutions are individually composed to answer the requirements and are presented in detail in the following sections.

E. Middle East Technical University (METU)– Trailing Edge Concept

The METU concept has been designed as an completely unslotted and closed trailing edge. Due to the concept a high strain capability is needed in chord wise direction in the area of the connection to the rigid wing box. The location of this element of an elastic connection is between wing box panels and trailing edge panels. Poison's ratio effects had to be reduced to a minimum as they would result into span wise contraction and extension. Due to these coupling effects wrinkles could disturb the airflow on the aerofoil.

The trailing edge panels are made from thin glassfibre reinforced epoxy resin (Figure 10). This is a baseline material also included in the materials and compliance matrix. The material is a prepreg and can be co-cured with elastomers at discrete locations to allow for flexible links. The GFRP can be tailored in thickness to achieve different stiffness distribution for the deflection of the trailing edge and load introduction points. The used GFRP prepreg had a curing temperature of 125°C and could therefore be used in co-curing process with EPDM as well. The elastic link was originally designed to be made from EPDM locally reinforced with high modulus carbon-fibres. However the material showed a stiffness being too high. As good results were made in the pretests using a pouring silicone the silicone was chosen over the EPDM for its better strain of up to 500%. Although the solid GFRP attachment points were tapered the thin silicone skins would tear. A thicker version of the skins on top and bottom resulted in to high actuator forces.

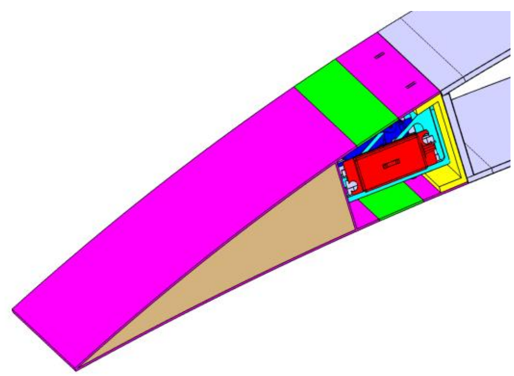


Figure 10: The CAD-model of the original METU-TE design using two compliant skin areas (green) and five actuators

As a consequence of these trials the upper silicone skin was removed and replaced with a bending 0,25mm GFRP layer to create a fixed link on the top and a flexible silicone link on the bottom of the morphing trailing edge. To allow for a better movement of the actuators on the inside the top two servos were removed to stop the servos from blocking each other due to small manufacturing deviations.

The very limited space and the precocious design of the original METU-TE did not allow for this concept to function on this scale. The tests with the redesigned concept seem promising but are not finalized by the time of the publishing of this paper.

F. Technical University of Delft (TUD) - Leading and Trailing Edge Concepts

The TUD leading and trailing edge concepts were designed using conventional elastic epoxy based GFRP and single overlapping slots on the bottom of one of the skins. These concepts allow also for twisting along the span (Figure 11). Bending loads are applied as well as twist. The morphing element edge panels are made from thin glassfibre reinforced epoxy resin (GFRP). A secondary bonding process is applied to connect upper and lower panel by an elastic lid. The elastic lid is an edge filling made from elastic adhesive. This allowed for a small movement of upper skin against lower skin and thus a transfer of shear loads at the trailing edge when twisting it. As the upper panel is fixed to the wing box, the lower panel is introduced into a small gap at the lower surface of the wing box. The actuators can move either in one direction to bend or in opposite direction to twist the trailing edge.

The leading edge was designed similarly; however no bondlines were needed due to the bending load supportive shape. The deformation of the TUD-LE is realized by sliding the lower part of the LE skin back- and forward. In order to keep the lower moving part from indenting the skin is supported by moving spacers which are connected to the spar by 3D-printed aluminium connector brackets and ball links. The actuators are mounted to the bottom of the skin and move along with the bottom of the skin while the top part is clamped to the wing box.

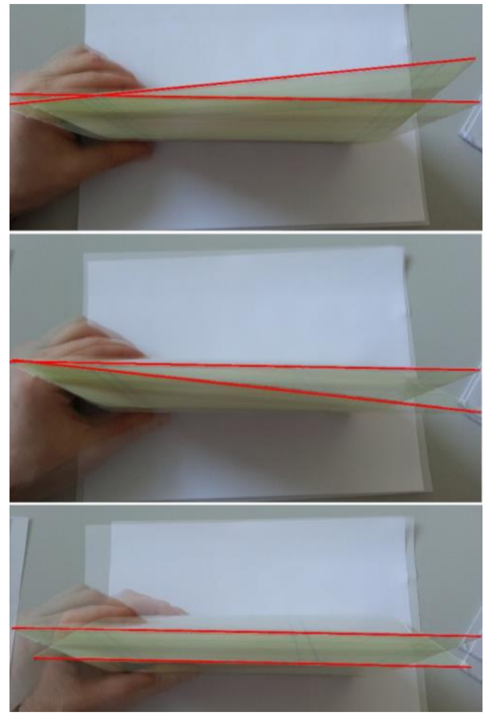


Figure 11: Overlayed positions of possible morphing for the TUD-TE concept using conventional epoxy prepregs

G. Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) – Leading Edge Concept

The DLR concept envisaged closed leading edge with a flexible leading edge skin and a bolted connection to rigid wing box areas (Figure 12). The bending loads to the skin resulted in high strain loads in chord wise direction. Poison's ratio effects had to be reduced to a minimum as they result into span wise contraction and extension. Due to these coupling effects wrinkles could disturb the airflow at the aerofoil. This area of the wing is in higher risk to see impact damage as other areas of the wing, however through the use of an elastomeric cover layer the thin structural layer was protected well against "hard landings". A Certain stiffness is needed for load introduction to deflect the leading edge and to withstand the aero-loads. The used omega stringer fulfils the task to stiffen the skin in spanwise direction and allows load introduction.

The leading edge is made from a multi-material setup. The used materials are also included in the materials and compliance matrix. The thin unidirectional epoxy-glassfibre prepreg can be tailored in thickness to achieve different stiffness distribution for the deflection of the leading edge and load introduction points. The application of these layers gives robustness to impacts as well as the further thickness reduction of the prepreg layup is possible. The so-called ePreg developed in this project is a semifinished product made from elastomeric matrix (EPDM in this case) and oriented fibres. Prefabrication allows for larger sheet size with constant material quality. Either fabric or unidirectional oriented fibres are possible to process.

Figure 12: The DLR-LE with a ridgid ends for the clamping to the aux spar, a foam core omega stringer and a combination of a epoxy prepreg structure and elastomeric cover layers

H. Universidade da Beira Interior (UBI) – Span morphing Concept

The UBI concept was designed as a telescopic wing span extension. The concept needs rigid wing box areas. The wing box has one fixed part and a movable part. Both elements are rigid boxes, with the need for high stiffness and lightweight design. The used materials are also included in the materials and compliance matrix. Different carbon fibre fabrics are available to produce the face sheets of thin sandwich panels. The sandwich core is expanded foam which can be tailored for different sandwich thicknesses. The spar caps were made from pultruded material, introduced into the foam. The project partner UBI successfully presented the material setup with a conceptual demonstrator including the sandwich produced and a kinematic to extend the span. As this material concept is very mature, no special skin development was needed.

I. Swansea University (SU) – Span morphing Concept

The SU concept is a wing span extension with a very elastic skin, capable of bearing very high strain rates in span wise direction (~130%) combined with no lateral contraction (in chord wise direction). Adding to this, the skin had to be tough enough to withstand aerodynamic and environmental loads. At the moment the ePreg material with EPDM designed by INVENT for the morphing concepts of CHANGE cannot reach the needed high strains for this concept. In order to attain the strains needed a different elastomer matrix had to be chosen. The process for the manufacturing of the skin is completely different as the silicone is not compatible with the curing process of the epoxy based prepreg. The Elastomer Matrix Composites (EMC) designed by SU allowed for very large strains (> 150%) with low Poisson's ratio ($\nu \approx 0$). However, the EMC approach for this very specific morphing application is a premature process by bonding thin silicone sheets on both faces of a carbon fibre unidirectional dry material.

Further evaluation by both SU and INVENT regarding optimization is needed to find a way to fully surround the embedded material, which is placed locally to prevent the caving in between the ribs. In order to realise the structural and aerodynamically needs several critical points have to be investigated and kept in mind when designing the skin:

- Rib/skin interface - separating and locally supporting elastic skin areas
- Solid wing/skin interface - smooth yet removable connection
- Acceptable actuator loads - weight/force ratio
- Acceptable caving under load - to which degree is a caving-in aerodynamically acceptable

Due to the immaturity of the skin the SU span morphing concept is to be further investigated but was not considered for the flight tests.

V. Skin tooling for morphing skins

The leading and trailing edge devices in CHANGE demanded for an adapted tooling concept. Due to the widespread material combinations of the different morphing devices a concept had to be found, which suits the needs of thermoset resin system curing parameters as well as vulcanizing of synthetic rubbers and silicones. As required from the material combination both materials had to be processed according to their specific needs at the same time.

Based on the curing/vulcanizing properties a tooling material which can withstand the thermal and mechanical loads had to be found. Table 2 gives an overview of the concepts and the characteristic materials that were intended to be used and also gives an overview of different curing parameters for skin materials /combinations proposed by INVENT to the designers of the morphing skins.

Partner / Concept	Material proposed	Curing temperature	Curing pressure
DLR / leading edge	glass prepreg with thermoset matrix; synthetic rubber; c-fiberPrepreg with elastomeric matrix (INVENT's "ePreg")	125°C	7 bar
TUD / leading edge	glass prepreg; sandwich stringers	125°C	2 bar
TUD / trailing edge	glass prepreg;	125°C	2 bar
METU / trailing edge	glass prepreg with thermoset matrix; synthetic rubber/silicone; c-fiberPrepreg with elastomeric matrix; foam core in ridged areas	125°C	7 bar

Table 2: Important process parameters for the tooling design

In order to design a tooling system which could resist these parameters (the combination of temperature and pressure) and was durable enough to produce an unnamed number of parts the material of choice was a metal alloy. Due to INVENTs experience in the production of composite parts and the machining of the tooling for these parts aluminium was chosen as base material for the moulds. Thus allowing a maximized flexibility regarding the usage of different materials for the morphing devices. A further advantage of metal tools is a variable use of release agents and their application as well as very good properties regarding the sealing for the vacuum bagging.

However due to the shape of the leading edge section of the NACA6510 a negative metal tooling could not be manufactured in a single piece without creating problems for the demoulding of the part. A two piece mould would create a surface marking which was unremoveable, especially on the elastomeric surface in the area of the aerodynamically important stagnation point of the DLR-LE design. The solution was a slightly flexible mould made of CFRP-prepreg. After tempering the mould and covering its mould surface with a PTFE film, it was possible to use the mould at elevated temperatures and pressures, without creating a surface marking. The afterwards applied PTFE film allowed the processing of the synthetic rubber EPDM together with the epoxy based prepreg resin.

ARA provided the airfoil coordinates of the NACA6510 along with the loft of the loiter wing. Using these coordinates CATIA V5 allowed to transfer these points and to create a spline using the embedded module. The spline is created for the complete airfoil and had to be trimmed down to the leading and trailing edge contours. The rendered spline was then used to create a first cross cut section of the mould. Since the profile is untwisted in the morphing area a linear approach was used.

After specifying the mould surface which is equivalent to the part surface, separationplanes had to be positioned. Since the parts for the morphing elements in the CHANGE wing were rather small sufficient accessibility had to be ensured in order to be able to place material layers exactly and minimize manufacturing deviations from the beginning on. A tooling consisting of an upper and a lower part allowed for a maximum accessibility of the mould surfaces. The placing of the separation plane for the trailing edge left only one logical option as shown in Figure 13 separating the 2mm gap in half. This also enables INVENT to manufacture the two halves separately and later join them using an elastomeric adhesive or silicone, depending on the morphing designs of the Partners.

A separation plane will always leave a small mark on the surface of the part. For the trailing edge this was acceptable since the very end of the trailing edge would be post processed.

After the machining of the tool parts they were aligned and bolted with M10 bolts. The bolts were flush-mounted and the holes were filled with silicone to protect the vacuum bagging. The position was secured by drilling holes and the use of tapped dowel pins (ø=8mm). The surface roughness of Rz=6,3 will result in a sufficient surface quality for post processing and painting in the paint shop. Following the DLR-LE-Concept with an integrated (omega) stringer the tool is designed “upside down” to allow better handling and positioning of the stringer. For the leading edges the positive master mould was used to place the layers with a higher precision and wrinkle-free. Table 3 shows an overview of the tooling masses and dimensions.

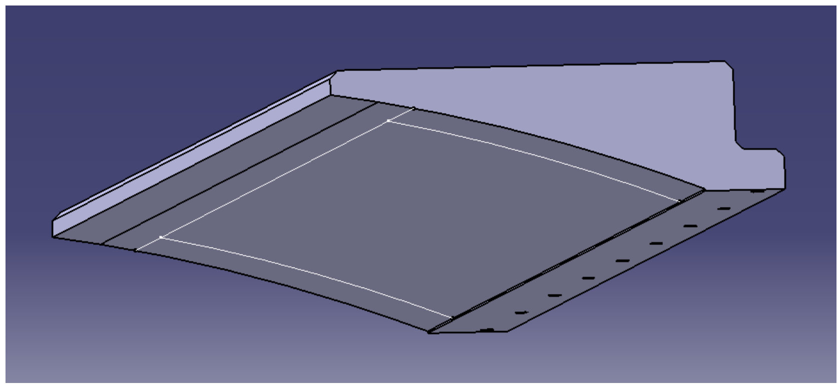


Figure 13: Tooling for the casting of the upper surface of the NACA6510 trailing edge. The white lines indicate projected engravings on the mould surface to allow accurate post processing.

VI. Manufacturing the skin of the morphing elements

The CAD-data provided by the DLR and TUD for the leading edge and by TUD and METU for the trailing edge was used to produce the first set of prototype morphing elements for the wind tunnel testing of the 1/2-span model. The manufacturing process of the morphing leading and trailing edge for the CHANGE-morphing wing was adapted with a series of manufacturing pretests.

Tooling	**Mass [kg]**	**Overall Dimensions [mm]**
Leading Edge Master Model pos.*	42 **(Metal)**	1100 x 270 x 125,9
Leading Edge Assembly neg.*	4,8 (**CFRP)**	1000 x 250 x 115
Upper Trailing Edge	36 **(Metal)**	1100 x 281,4 x 79,6
Lower Trailing Edge	12 **(Metal)**	1100 x 280 x 49,3
Trailing Edge Assembly**	48 **(Metal)**	1100 x 281,4 x 109,6

Table 3: Overview of masses and dimensions for the tools (*one piece / **without bolts and pins)

The knowledge and the experience gained in the manufacturing of the prototype morphing elements and the wind tunnel testing was used to manufacture the morphing elements for the flight model. The manufacturing of the UBI span extension is not described since it was manufactured by Tekever / UBI.

Figure 14 shows the a raw part of the TUD-LE design with the conventional material approach manufactured in the multi-purpose flexible CFRP tooling and the aluminium master mould. The TUD trailing edge concept was manufactured simultaneously with the TUD leading edge but in the aluminium trailing edge tooling. After creating a flat projection of the surface of the LE and TE in CATIA V5 R21 a .dxf-file is prepared from which EHG250-68-37-Prepreg layers were cut on the CNC-cutter. These layers were then placed in the female moulds of the upper and lower shell of the TE respectively the positive master mould of the LE. Peel ply, release film and breather weave were applied and secured in place (Figure 15) before sealing and evacuating the mould set. After the autoclave curing process the raw shell parts were cleaned and cut to size on a circular saw with a diamond coated blade according to the engravings and drawing derived from the partners CATIA-Models. The cuts for the raw dimensions were placed exactly on the raised engraving (a negative engraving in the mould results in a raised engraving on the part). Half of this engraving was left for repositioning the shells in the female moulds. The male slot geometry was cut into the wing box facing element of the lower shell element. Before bonding the upper and lower shell with two component structural adhesive, the last 15mm of the raw parts were sanded and the complete part was cleaned with IPA before repositioning and fixing the shells in the mould.

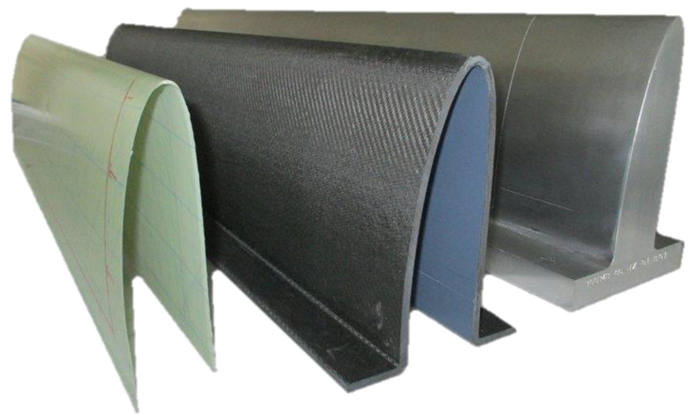


Figure 14: 1st prototype part of the TUD-LE (l.); composite female mold (c.); aluminium mastermold for the morphing LE-elements in CHANGE (r.)

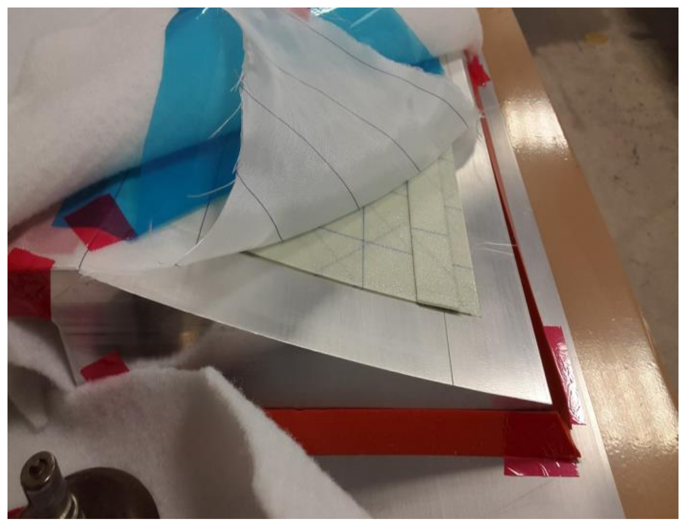


Figure 15: The upper shell of the TUD-TE before the sealing for the autoclave cycle

All parts except for the DLR-LE were painted with 2K-epoxy coating (Figure 16) with the paint containing elastifier which was used to prevent cracks in the highly strained areas of the morphing elements.

The DLR-LE used a premanufactured solid foam core omega stringer for the load introduction to the skin thus an approach as it was used for the TUD-LE is unfeasible. The skin layers were placed starting with the layer closest to the stringer until the outer most layer was positioned on the positive master mould. The layer package was then taken in its curved shape and placed inside the very limited space of the flexible CFRP mould. Since the layers were already in the curved shape, only little repositioning was necessary thus avoiding wrinkles in the laminate (Figure 17). As with the other morphing elements the parts were manufactured with excess space for the final trimming to end shape. The combination of the elastomeric material and the epoxy prepreg however did not allow conventional cutting since the saw introduced vibrations which then lead to delaminations. An oscillating tool has so far shown the best results in post processing this material combination since the cut is done by grinding through the material rather than cutting.

The METU-TE was manufactured similar to the TUD-TE, but whilst joining the upper and lower shell in one autoclave cycle. The complete structure including the foam core of the rigid area and the load introduction points (filled with core filler) was cured in one autoclave cycle. The compliant areas were manufactured from pouring silicone. These areas connect the rigid parts (connection lap and rigid part of the trailing edge).

The METU-TE is representing the multi-material-TE-concept. During the manufacturing a series of design elements had to be adapted to allow manufacturing in the first place. The METU-TE-Concept is ambitious using the compliant silicone skin in the area of the control surface. Further tests, along with design changes would have to be made for the flight test model.

VII. Performance of the utilized material

Even though the cyclic testing of the skins is still ongoing (in the test stand shown in Figure 18) the first overall results for the skin materials seem very promising. The tests were designed to mirror the structural and environmental loads as they could appear in realistic scenarios. The movement of the morphing elements was broken down into the single cycles. One cycle represents the deployment and the retraction of the morphing element. For the test design the information provided by TEK was used to set a first test scenario. For example an annual flight time of about 350 flights and four to six deployments per flight was used to estimate the loads. From the first test results the skins show sufficient fatigue resistance for the designed morphing scenarios (for profile morphing devices ensuring a safety factor for the aerodynamic loads).

The conventional skins (designed by TUD) showed very good results and basically no failure growth after 10k cycles at ambient conditions (23°C / 40%$_{rel}$). Due to the high curing temperature of the glass fibre prepreg the material should not show any signs of degradation due to the test conditions for environmental loading (60°C / 55%$_{rel}$). The impact of high UV radiation has to be evaluated after the tests however only little impact on the structure is expected due to the surface UV resistant coating.

Although the METU-TE promised the best performance regarding the aerodynamic effectivity and has shown a very mature design for manufacturing the very limited space in the trailing edge has made assembly problematic. Due to these circumstances the METU-TE has been evaluated as not suitable for the cycling tests and is being redesigned to allow the capturing of the motion with a ARAMIS system.

Upon the multi-material approaches the DLR-LE skin has shown exceptional performance with no failure at all. Even the surface deviations in the elastomeric layer have not grown over the 15k cycles tested yet. The elastomeric cover layer protect the very thin (0,375mm) structural layer in a manor that even resin cracks have no impact on the overall behaviour. The tests with environmental loading will reveal if the elastomeric/thermoset material combination is suitable for the harsh surrounding conditions of the sought deployment.

Figure 16: Flush fit of the TUD-TE slot plate and the integrated doubler on the upper shell of the TE (top) and the TUD-TE-Element ready for delivery to TEK where mounting to the wind tunnel test wing was done (bottom)

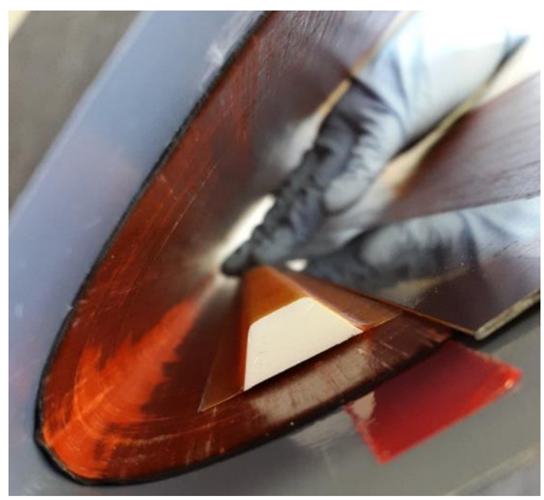


Figure 17:Placing the premanufactured solid foam core stringer in the very limited space of the DLR-LE

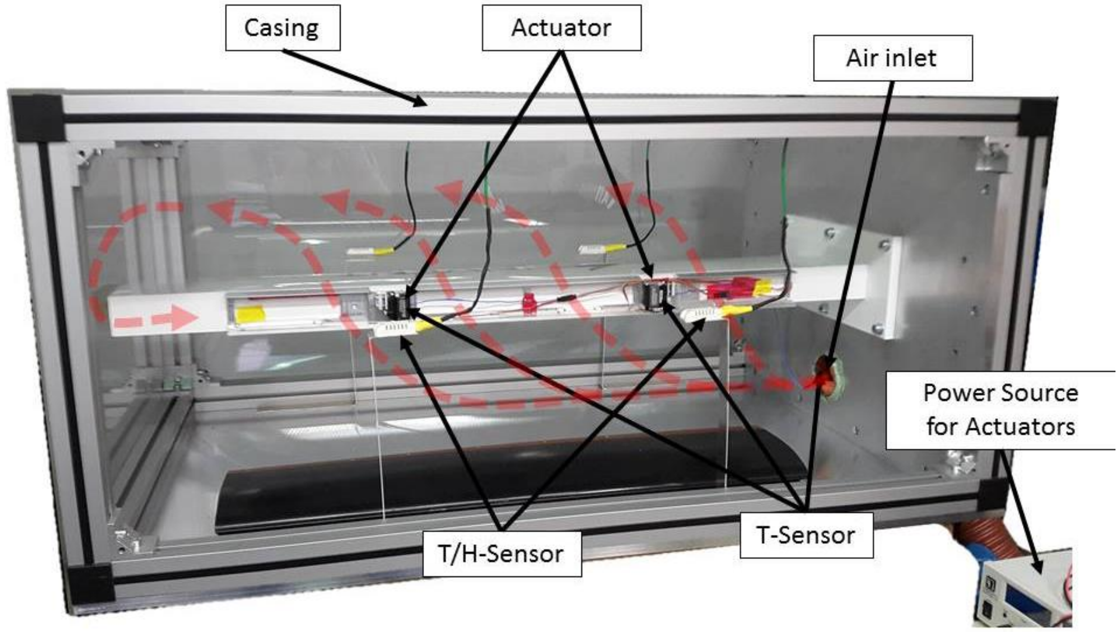


Figure 18: The test stand box for the skin testing at elevated temperatures, high humidity and UV radiation. The set up includes several sensors for actuator temperature, temperature at the air inlet and humidity/temperature in the box. In the rear of the wing box the TUD-TE is fully integrated for the testing (Not shown are the UV radiator and the heater system).

VIII. Conclusion

For CHANGE several horizon broadening steps have been taken by INVENT to allow for future morphing airfoil designs. Based on the morphing elements designs of the CHANGE partners a material database for morphing applications has been established. The material combinations were tested with newly designed material test standards for elastic composites. The test results then were used to make first estimations on the behaviour of the prototype morphing elements for leading and trailing edges. The prototypes were manufactured at INVENT, thus extending the experience and the "know-how" about the processability of highly elastic composite materials. Following this important step the morphing elements were tested in a specially designed test stand to evaluate the cyclic behaviour and the impact of environmental loads such as high temperatures and UV radiation.The next steps include design proposals for a simplification of the fully integrated kinematics. This step has high relevance especially for morphing elements with minimal internal space like the ones in CHANGE. In order to optimize the performance of the skin elements a tapering of the skin lay up will be proposed to allow an ideal deformation of the aerodynamic shape and minimal actuatorforces.

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References

1. **Gamboa, P. and Santos, P.** *Telescopic Wing-Box for a Morphing Wing.* Universidade da Beira Interior, Covilha, 6200-358 Covilha, Portugal 2015 : AIAA, 2015.
2. **Hexcel Corporation.** TDS HexPly®913 - Product Data. s.l. : Hexcel Corporation, 2007.
3. **Grafil Inc.** TDS Typical Fiber Properties PYROFIL™TR50S 15K. Sacramento, CA : Grafil Inc., 2010.
4. **Gurit GmbH.** TDS EHG250-68-37. Kassel : Gurit GmbH, 2007.