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TECHNOLOGY INTEGRATION FOR ACTIVE POLY-MORPHING WINGLETS DEVELOPMENT

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ABSTRACT

This article presents the preparation of a working physical mock-up wingtip device with morphing functionality. The objective of the mechanical demonstrator is to achieve a technology readiness level to establish confidence that one would proceed to an in-service R&D initiative. To establish the feasibility of scalable technology integration for product development, a tier schedule is employed to demonstrate material compliance, mechanism kinematics and perform bandwidth experimentation. Potential composite materials for design of flexible skins (i.e., Hexweb®, Kevlar® 49 and HexPly®) were assessed using a spectrum of experimental verification procedures. These results are embodied to benchmark qualitatively and quantitatively the mechanical performance of the potential materials to use in a preliminary optimized morphing schedule.

INTRODUCTION

The objective of this project is to investigate the use of compliant materials and structures technology to change the shape, trim and incidence angle of winglets during flight. The envisioned multi-phase mission performance, along with manoeuvrability and integrated economics (e.g. 5-6% augmented vehicular efficiency throughout the operational flight envelope, compared to 3% for current fixed winglet designs - see Fig. 1), can be translated into a large spectrum of consequential benefits, such as: the adjustment of trim angles over the cruise range, optimise lift to drag ratio to increase flight stability at low speed operations, consequently reduce community noise, allow a higher payload through better engine-out performance, adjustment for different flight phases (climb, cruise & descent), improve performance during abnormal procedures, improve flight stability during normal and direct flight control system modes, improve aero-elastic performance, to name but a few.

Within the MORPHing WingLETs project (MORPHLET), a tier schedule is employed to establish feasibility of technology integration for investigation of a multi-phase flight adaptive winglet system. The first steps of the hierarchical methodology towards the product development included the technology selection [2] (i.e., feasibility of actuators performance indices followed by a multicriteria and multi-step weighted performance appraisal). Concurrently, a preliminary optimization study of non-planar wing systems, scheduling for a narrow body aircraft

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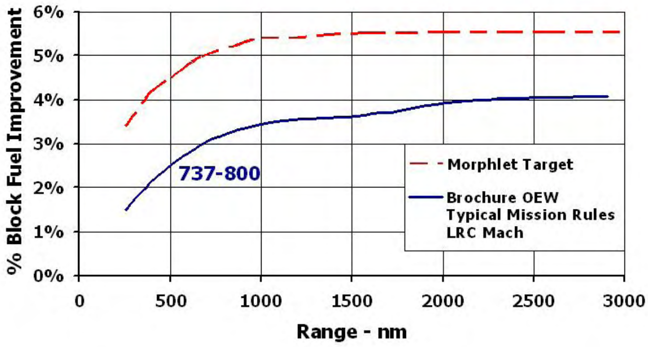

Figure 1. Prognosticated improvement envisioned for an adaptive wingtip system compared with 737-800 design case from Ref. [1].

platform was performed, outlining the integrated (3-phase flight) performance: climb-initial and cruise-descent in-plane span increase, step-cruise segments 67° cant (stow to meet ICAO Code C - 36m box with 0° cant. The geometry schedules include cant and twist variations, whilst the camber was fixed due to results in preliminary analyses.

Further steps in the Tier schedule describe a preliminary experimental investigation of potential composite materials for use in MORPHLET skins. In particular, the aim is to characterise potential skin materials and structures in bending and torsion to enable an assessment of their benefits to the MORPHLET project. The objective is mainly to understand the important features of the skin materials, based on multiple quantitative and qualitative assessments of mechanical performance using the MORPHLET schedules, rather than to give a database of material properties. To aid understanding and to aid the design of the actual MORPHLET skin, the experimental work has been supplemented by finite element modeling to benchmark complex structural behavior.

This study also mimics contemporary fixed-winglet integration, i.e., retrofit the active poly-morphing system[1]. A half-scale wing incorporates features for morphing capability, whilst some structural components and systems are retained from the original fixed wing (e.g.,stuffed-wing-up to termination of outer wing tank, aileron and control system, surge tank). Some modifications to the fixed wing structure and systems are also envisaged to develop the active integrated non-planar component (e.g., removal of the leading edge device, anti-icing feed-telescopic bleed air duct to piccolo tube, flight control system-control laws, introduction of additional hydraulic lines to support morphing capability, fail-operational system).

Experimental and Numerical Investigation of Materials for MORPHLET

MORPHLET requires a light weight design with high deformability. Furthermore the compliant morphing structure is subject to complex loading from both the aerodynamics and the structure. A key issue in this approach is the design of a suitable skin with conflicting stiffness properties that allow alterations in shape based on the aerodynamic requirements (i.e. compliance), yet is able to support the aerodynamic loading (i.e. stiffness).

Morphing skins are the largest problem associated with adaptive wings, allowing shape changes for requisite aerodynamic features, whilst delivering compliant properties with a sufficiently stiff structure for aerodynamic loading. This work presents a simplified approach to morphing skin evaluation. By breaking down the complex structural behaviour into the main analytical forms of the deformation field, i.e., due to bending and twist (n.b., these are considered in the context of MORPHLET loading, where bending occurs due to change in cant angle of consecutive panels and twist due to differential change in cant of the main spars).

A series of standardized experimental tests are employed to investigate skin material candidates, along with numerical vetting[2] to establish the skin capabilities within a multi-disciplinary environment, and also determine their suitability for selected critical areas for subsequent test verification. The experimental investigations include four point bend flexural tests and twist deformation and highlight trends of the deformation field and correlation with numerical models. The main objective is to identify the variability of the structural response of the candidates and the design allowable testing performed to satisfy structural substantiation requirement. Although a rigorous material qualification testing would be required for candidates for MORPHLET schedules, this investigation only screens potential materials in an initial evaluation of key material properties by means of structural response, before planning subsequent complex testing.

The effectiveness of key material properties usually expressed in terms of figures of merit such as strength-to-density and stiffness-to-density ratios (see Ref. [4]), dictate the choice of application design but may not provide the required properties of a material under complex design configuration and loading functions. Consequently, a number of different materials (a combination of fibers and matrix) are investigated in this paper that cover a large diversity in the specific strength and stiffness spectrum, i.e., carbon fiber reinforced polymer (CFRP) M21, E-glass 913G-E, Kevlar®49 and a standalone aluminium Hexweb® Flex-core honeycomb (highly flexible with unique cell configu-

[1] A morphing taxonomy usually refers to iso-morphologies (i.e., combined scheduling of localized uni-directional geometry change) and poly-morphologies (i.e., adaptation of morphologies and external geometry that has more than one shape). Therefore, an active poly-morphing system, encompassed within the latter category, refers to a multi-directional geometry change according to the design intent

[2] Here, a finite element analysis is performed using the commercial software package ABAQUS 6.7-1® is used for finite element analysis [3].

ration that eliminates anticlastic behaviour).

Bending Test

A series of experimental investigations to examine the flexural properties of a number of composite materials have been conducted and presented. The experimental research is focused on the bending capability of various ply lay-ups and is established from standard test method ASTM D 6272-02 [5]. The objectives of this investigation are to:

- Provide force-displacement information required for evaluation of the composite materials;

- Identify the deformation and range of flexibility, i.e., failure initiation of potential skin materials;

- Evaluate and validate the numerical modeling of coupon samples against experimental results to enhance further complex testing.

The testing apparatus requires a specimen to be placed on two pivots, with a force applied by means of two indenters at a constant speed of 2mm/min in the centre of the specimen (n.b., a configuration with loading at a third point has been used and the load span is determined by the specimen dimensions as stipulated by the test standard ASTM D 6272-02).

The testing machine used is an electromechanical biaxial tension/torsion apparatus (Roell Amsler HCT 25). The machine is able to apply a vertical force of 25kN (in)dependently of a torque about the vertical axis of 500Nm (the latter attribute shall be used in the subsequent tests). The test apparatus was previously calibrated so that it can operate at constant rates of crosshead motion and was equipped with a deflection measuring device for the crosshead. The machine was also equipped with an external linear variable displacement transducer (LVDT) to measure the deflection at the center of the loading span.

A computer terminal is linked to the machine by means of an Instron 8800 controller/data logger to drive the test (i.e., control force, torque or axial/angular displacement precisely within set rates and limits) and record the data. All specimens were loaded to catastrophic failure (i.e., rupture in the outer fibers) or the physical limits of the transducer were exceeded, at which point the crosshead displacement was halted and the load removed. Specimens were carefully mounted on the machine and during the test were monitored to ensure a consistent data was logged through the correct positioning the LVDT is achieved.

The failure modes in the laminated composites in FEM have not been investigated, since failure criteria are beyond the scope of this study. But they certainly affect the displacement history during loading and can identify ranges of nonlinearity, suitable for the MORPHLET target application before damage has occurred. Failure modes are strongly dependent on the geometry, loading direction and ply lay-up, and are distinguished by their different forms, i.e., in-plane and transverse failure modes, which can be obtained by a cumulation of different mechanisms, such as matrix tensile cracking, matrix compression, fiber breakage, fiber matrix shearing and fiber buckling. For flexural testing, the following materials have been used:

- HexPly® M21 (high performance, very tough epoxy matrix for use in primary aerospace structures) with fiber T700GC and mass 268gsm;

- HexPly® 913G-E-5-30%, a unidirectional (UD) E-Glass Epoxy prepreg.

Prepreg curing conditions stipulated in the data manuals from Hexcel® were followed. Both materials were tested in two and four ply configurations, 'length-wise' (principal axis of anisotropy) and 'crosswise' (90 deg to the lengthwise direction), i.e., [0/0], [90/90], $[0/90]_s$ and $[90/0]_s$. To mitigate large variability in the specimens (see Ref. [6] for 'within-batch' and 'between-batch' sources of variability), the specimens were cut from the same molded plates and then polished to the desired finished condition.

The occurrence of flaws in components is unavoidable during material processing, fabrication or service because of real bounds on the quality control and modeling [7]. These include cracks, metallurgical inclusions or voids, design discontinuities, defect microstructure (e.g., fiber misalignment), cross-link density or some combination thereof. The magnitude of flaws induces unexpected structural behaviour, and thus a large number of test specimens is desired to draw appropriate conclusions. These flaws can prematurely initiate bending failure into specimens where regions may exceed a certain allowable stress in tensile or compressive components. Flaws also dictate the non-uniformity of stress distribution that can cause failure and variability in designs.

Most material properties of composites are dependent on the relative proportion of reinforcement and matrix that can inherently vary within a sample population. This is due to locally changing fiber volume, rather than due to variation in the fiber, matrix or fiber-matrix interface (n.b., the relation between property and fiber volume is essentially linear).

Variability in structural behaviour of the candidate composite materials may also result from run-to-run variability in testing and geometry specifications, due to inherent variation in their processing. Consequently an additional source of uncertainty can be referred to as "between-panel" variability. This uncertainty may be predicted since it becomes measurable by means of shape cut tolerances (e. g., the specimens achieved a width tolerance of max 0.6% during processing). These percentiles may have a dramatic impact on the overall structural behaviour, and a sensitivity analysis of this form of uncertainty may be used to determine the suitability of the nominal width.

The above mentioned variability in composite material properties must be considered during the assessment and validation of their structural integrity, by means of loading behaviour and FEM calibration. It is important to identify the components of such variability when designing composites subject to complex loading functions, in order to set design allowables to satisfy substantiation requirements, also to make use of validated FEM analyses in selected critical areas where testing would not be possible. Therefore an FEM validation is needed first to fully augment the selection of composite materials. Although this paper only investigates material properties required for MORPHLET schedules (see building-block approach in Ref. [6] for design development testing), it also presents a preliminary numerical approach to coupon testing by means of the FEM. But the validation of the FEM requires the identification of the level of uncertainty present in the coupon testing, and clearly drives the test assessment towards the practicality of numerical methods versus standard analytical methods.

Fig. 2 shows the absolute and relative error in displacement and highlights the ability of the current FEM predictability. Error percentiles can constitute a metric in a calibration and optimization methodology in order to minimize the error scatter and improve the FEM calibration. The figure shows graphical metrics to outline the feasibility of composite materials for morphing capability and concludes the use in the subsequent design steps of the corrugated skin, due to its potential 'adaptable wing' suitability: lightweight, durable, impact resistant, high stiffness and strength with low density, and displays a large longitudinal and transversal stiffness ratio [8].

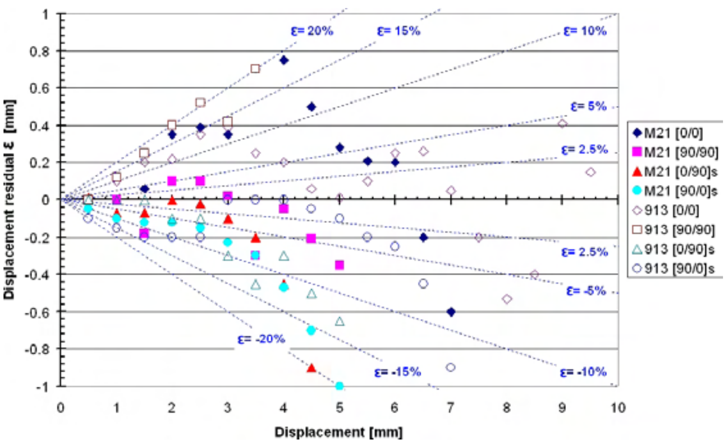

Figure 2. Absolute and relative error in displacement in Four point bend test of candidate materials.

Torsion Test. For torsion testing, a flexible material is chosen: Hexweb® Flexweb 5052/F40-0.0013 with Aluminum walls, in a specific cell configuration that eliminates anticlastic behaviour and permits small radii of curvature without deformation of the cell walls or loss of mechanical properties .

In each experimental torque test, the samples undergo an elastic loading before settling into a nonlinear large-strain regime, where the sections towards the rotation axis buckle, whilst the outer vertical edge of the specimen are in tension. During the tests, it has been observed that due to the high load cell capacity of the machine, compression through the crosshead occurred (the amplitude was 1% of the specimen's length), which caused inner sections to buckle. As such, a diagonal stress field is formed which alleviates the highly strained outer sections in terms of tension, lower the stiffness of the specimen which then accelerates the crushing and crippling of the specimens. This observation helps to explain the large discrepancies between the experimental and numerical results, since the FEM model only allows for rotational degree of freedom (see Fig. 3).

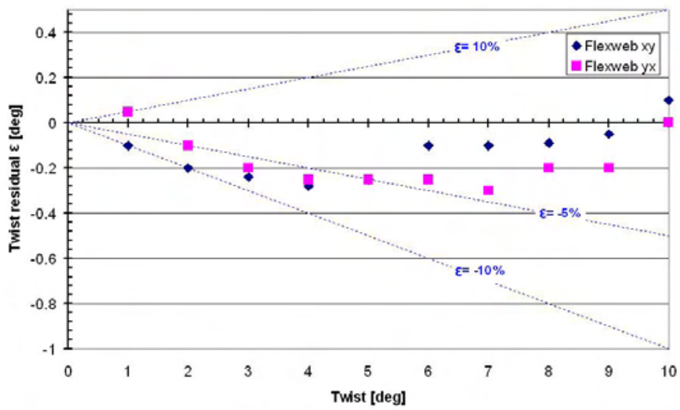

Figure 3. Absolute and relative error in torsion test of flexible skin.

The lack of conformity of the torsion simulation has sources on the idealisation of the driving mechanism, augmented by the need of accurate boundary conditions (the end tab procedure introduces imperfections in the experimental model that cannot be readily captured in the FEM model). The torsion test requires further investigation to establish the bounds on the variability in model required in subsequent steps towards the design of the MORPHLET (i.e., sizing and weight prediction). As a risk mitigation strategy, critical design parameters of the compliant mechanism are to be identified when coupling bending and twist due to differential actuation is a requirement for MORPHLET. However, provided the complexity of the compliant mechanism, the twist component can be alleviated by optimizing the load control path of the actuators. This can be achieved by imposing constraints on the critical degrees of freedom of joints, such that the bending of skins becomes dominant.

Mechanical Demonstrator

In order to establish feasibility of technology integration for product development, a mechanical demonstrator is proposed to mimic a narrow body aircraft platform. The scope is to benchmark validation of the solution through demonstration in terms of the design procedure, material compliance and mechanism kinematics. The objective of the demonstrator is also to perform bandwidth experimentation with emphasis on incorporating features for full-scale operational system in order to establish the potential for on-going development and consistency in assessing a technology's maturity towards an in-service R&D initiative. The mechanical demonstrator will provide an opportunity to incorporate lessons learned for full-scale, operationally compatible systems integration.

As a first tier development phase, a material compliance demonstrator was designed and constructed to expand the knowledge base regarding the polymorphic structures. This first demonstrator was to have all the necessary internal mechanisms to provide for the morphing shape envelope, but not the internal strength to support actual flight loads. The load case corresponding to flight load will be tested in a planned second tier demonstrator.

Several types of demonstrators and subsystems were considered. Finally it was decided to device a half scale outboard section of a high-speed transport aircraft (see Fig. 4). This wing partition will then have a root chord of 1.4 meters and a span just shy of 3 meters. Effectively this would simulate the aileron partition and a part of the outboard flap partition. The half-scale was selected in order to have appropriate minimum gauge in the construction materials and still have a large size device.

In a previous study [2], a preliminary investigation to pose the morphing winglet problem as an optimization problem to maximize specific air range (SAR) was carried out. The study targeted an in-service narrow body aircraft for various operating conditions of its 1000nm nominal flight profile to identify pertinent morphing features of the non-planar wing system configuration. Within the design space, the optimum candidate schedules indicated a significant sensitivity of the performance metrics (i.e., SAR, induced drag and lift-to-drag ratio) with respect to cant angle(up to 0.52 rad) and twist (up to ± 0.055 rad) from the baseline model, and insignificant sensitivity to aspect ratio and semi-span of the selected partitions. The envelope of cant and twist drives the design case of the structural sizing of the configuration parts.

One of the preliminary design candidates was to use a full size wing partition, taken form a scrapped aircraft. This would have ensured compliance with in-line service materials and design methods. This idea was however abandoned due to the lack of availability of scrapped aircraft wings, as well as to lab space restrictions.

Several types of actuation system were considered: exotic materials, hydraulic systems and electrical systems. The exotic materials were down selected due to limited availability and to avoid crossover errors when testing the new surface materials. Hydraulic systems would have been the best match for next generation design and actual flight loads. These too were down selected, due to time constraints in designing the needed control system.

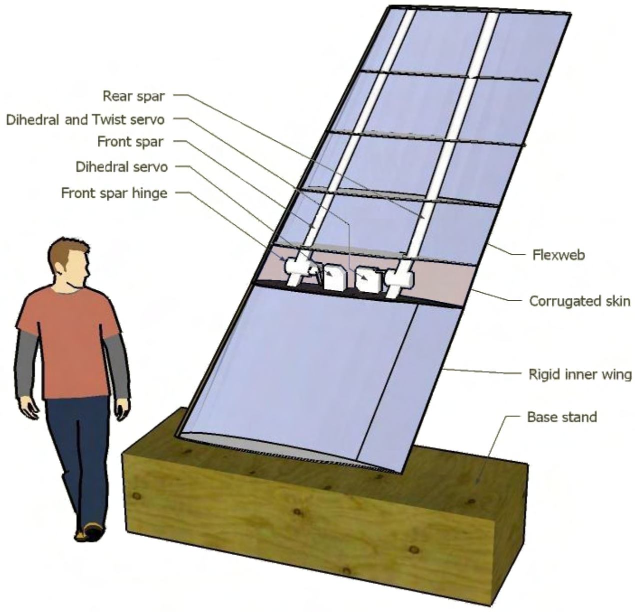

Figure 4. Virtual mock-up of the demonstrator.

The outlined demonstrator comprises four sub-assemblies:

1. Display stand and rigid-wing parts: rigid wing constructed as a monocoque design with marine grade plywood and will house the control the electricals;
2. Electrical and control system is composed of two sp105 power servos, scaled up versions of ordinary radio controlled servos, a Phidget motor control unit (MCU), an internal 12 volt power supply system, along with fuses, cables and switches;
3. Internal driving mechanism:
   - spars: box beam made of plywood;
   - front and rear spar hinges: rapid prototyping fabrication, are mounted at each spar and housed by the - corrugated skin - see Fig. 5;
   - servo seats: rapid prototyping fabrication, and are integrated within the hinges;
   - servo-hinge linkage: rapid prototyping fabrication; one servo per spar gives the requisite bending moment and by applying differential deflection, wing twist will be facilitated; torque linkage between servo horns and hinge moment exchange;
4. Morphing Skin:

- corrugated skin - the enhancement of the aileron-partitioned morphing skin is envisioned by the corrugated skin (see Fig. 7).
- outer partition skin: flexweb - manufactured in 5 separate panels: top/bottom trailing edge to rear spar, top/bottom rear-to-front spar and leading edge; access panel on the bottom side skin towards the tip.

The selected control and actuations system is electrical, utilizing standard RC servos and a pulse width modulation controller which can be directly controlled from a personal computer. This low power approach made it possible to use low yield strength materials in the internal mechanisms, which in turn made it possible to utilize a rapid prototyper for the manufacturing of pinions, gears, hinges, etc. The load on the internal components was well below yield stress for the material used. The limiting factor was the fatigue limit on the surface stress of the gears, which had to be designed with a low expected life time (MTBF 10h): a design decision well motivated by the fact that the level one tier prototype is not intended for endurance, or even long time testing purposes.

Figure 5. Servo-hinge linkage: rapid prototyping fabrication.

A special note is required concerning morphing skins by corrugation capability (see Fig. 7 for a coupon sample). In the literature for morphing skins a fiber reinforced rubber/elastomer has been suggested, which achieved stiffness in the fiber's direction and flexibility normal to the fiber. As pointed out in Ref. [8], this skin has low bending strength due to its minimal resistance to compressive instability. A special manufacturing process is required to produce composites in a corrugated form, following a non-sinusoidal wave pattern, i.e., perpendicular corrugation corners, as shown in Fig. 7. The material used for the purpose of this study was plain woven Kevlar, Du Pont styling 120 [9]. This material was chosen due to its ease of manufacture into corrugations and its potential 'adaptable wing' suitability: lightweight, durable, impact resistant, high stiffness and strength with low density. The corrugations followed a pattern of 4 mm height, alternating between lower and upper spacings of 8 mm. The manufacture of the corrugated Kevlar was achieved using a mould machined out of Aluminum, with dimensions: 1200 mm x 125 mm x 300 mm. A two-ply of Pre-impregnated Kevlar material was pressed into the corrugation mould and held in place using high temperature square section silicone cord, helping to maintain the desired corrugated shape during cure (see Fig. 6). Mould and Kevlar were vacuum sealed and placed in an autoclave following the 914/T300 procedure.

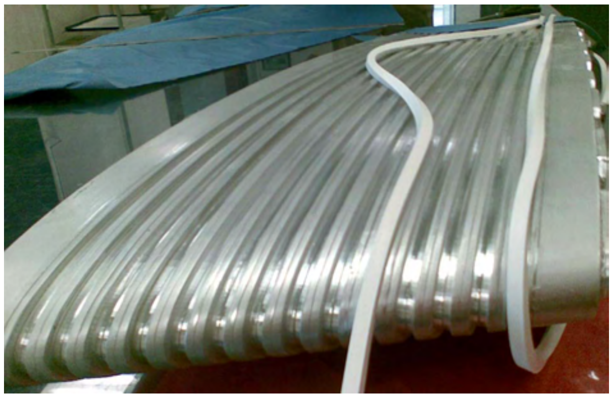

Figure 6. Aluminium mould for the corrugated skin.

A series of simplified numerical approaches of the morphing corrugated skin are employed in order to investigate potential lay-up configurations. Analysis of the tooling for the drape simulation is necessary to build up a strategy towards a feasible experimental behavior and numerical investigation resemblance. By studying a range of variation in the topology of the skin (i.e., fabric), one can generate manufacturing instructions and qualitative and quantitative measures of the feasibility of the selected fabric drapes. Variability exhibited in fabric drape is intrinsically linked to the geometry of the mould and fabric mechanical properties (i.e., anisotropic and nonlinear). Using a commercially available drape simulation software, the kinematic simulation of the manual lay-up process to set rules in terms of tow curvature (rate of change of shear), could not be established for the entire geometry. Yet, a split of regions at the trailing edge with similar in-plane tow curvature describing the manipulation direction, delivered ply sizes, but lay-up rules to the entire kinematic solution could not be determined. Thus, assistance on how to achieve the complex tow drape patterns in practice were not given. To explore these issues, a manual drape was carried out: the 914/Kevlar®49 prepreg was laid across the surface of the Aluminium mold (see Fig. 6) and smoothed down onto the slotted outer surface of the tool, requiring a substantial degree of manipulation. Intuitively, the manual draping with large ply sizes leads to defective lay-ups with heavily wrinkled regions at the leading edge of the tool (high curvature and taper), concluding that the limit of formability of the fabric used can be achieved with small ply sizes for a good drape pattern.

Figure 7. 914/Kevlar® 49 corrugated skin.

As this section identifies lessons learned in successfully achieving a mechanical demonstrator, a design performance improvement strategy is involved to validate the design procedure. Some performance assessment of materials through the finite element model (FEM) verification process, identifies a wide variety of factors that affect a realistic geometric deformation of the demonstrator. The strategy relates numerically determined topology lay-out configuration of the MORPHLET to the experimental designated one in order to improve/update elements of inaccuracy in the model (i.e., risk-mitigation paradigm). Such factors can be easily identified within the stiffening lay-out of the corrugated skin, which showed, in static loading case, a smooth geometric deformation, whilst a 0.52 rad dihedral and 0.055 rad twist change is reached. Figures 8 and 9 show qualitatively a step-wise improvement in numerical verification process from a standalone corrugated skin to a stiffened lay-out in order to avoid global instabilities, achieve constant span-wise deformation gradient and resemble the experimental model (see Fig. 10). Here, trends of the deformation field are highlighted to identify sources of inaccuracies and the need to update the model by means of stiffened sections to enhance shape adaptability.

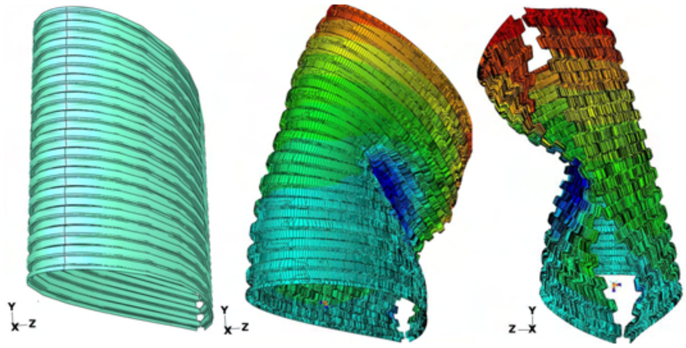

Figure 8. Numerical investigation of the corrugated skin showing buckling pattern on non-supported skin.

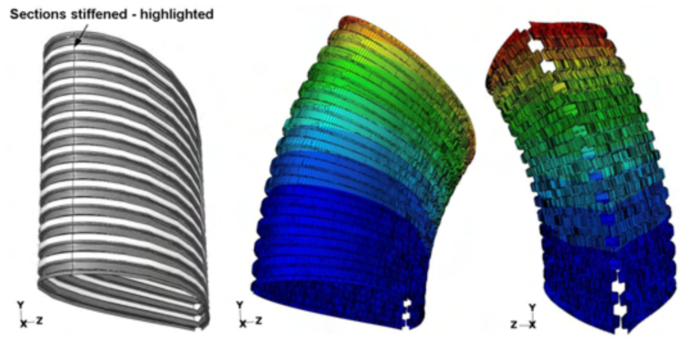

Figure 9. Numerical investigation of the reinforced corrugated skin (updated lay-out).

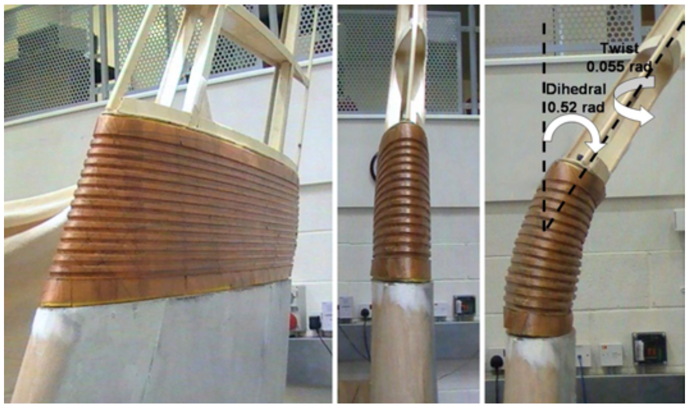

Figure 10. Rolled out and canted mechanical demonstrator (0.52 rad dihedral & 0.055 rad twist).

Conclusions

This paper has described a preliminary investigation of potential composite materials for MORPHLET skins in a series of standardized experimental tests (i.e., four point bend flexural procedure and twist deformation), along with numerical validation to set performance design criteria for use with MORPHLET programme.

Different levels of calibration are needed depending on the area of interest in terms of the displacement field. For instance, in the flexural test, very good agreement between the FEM and experimental results has been achieved (although only over certain level of the displacement field, due to the lack of implementation within the FEM of the non-linear mechanisms). Graphical metrics are used to enhance the understanding of application dependent composite materials. It was shown that the FEM predictability was fairly good for the two and four ply laminates, but concludes that the flexibility requirement can be met with a tailored longitudinal-to-transversal stiffness ratio of a corrugated topology. The torsion simulation identified sources on the idealisation on the driving mechanism, and shown in the case of the flexweb a good conformity with the FEM model to establish confidence in further investigation.

Further, a mechanical demonstrator is investigated to benchmark the feasibility and validation of technology integration and benchmark design methodology for full scale operationally compatible systems integration. A risk-mitigation design paradigm is employed in order to establish design performance criteria by means of numerical verification process and topology lay-out. The objective here is to also provide an opportunity to incorporate lessons learned in building a second tier demonstrator that targets a combined aero-structure compliance.

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