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Design and Manufacturing of a Multifunctional Thermoplastic Composite Leading Edge

G.F. Nino[*] , T.J. Ahmed, and H.E.N. Bersee[†]
Design and Production of Composite Structures, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 3, Delft, 2629HS, The Netherlands

The use of different types of fibers in woven reinforcements allows the introduction of multifunctional properties in composite structures. In this paper, a multifunctional concept based on an internal heating layer is presented. Thus, a controllable heat signal is used as ice protection system and enhanced non destructive inspection. Several parameters of the heating layer such as horizontal spacing and vertical position were evaluated. As an application case, a thermoplastic composite leading edge manufactured by thermoforming was developed. This approach has the potential to accelerate the implementation of MFS in current and future composite structures. Finally, the ideas presented on this paper can be extended to other type of components and to thermoset composites.

I. Introduction

A present challenge in the aircraft community is how to keep or enhance performance of current systems while lowering manufacture, operation and maintenance costs. In the effort to reduce weight and volume of components, researchers are looking to the area of multifunctional structures (MFS). MFS represents a new manufacturing and integration methodology and this concept has been credited to Obal and Sater [1] in the context of adaptive structures. In the most general terms, MFS are defined as structures that perform additional engineering functions beside the function of load carrying. The functions can be performed simultaneously or sequentially in time and seek to achieve overall system-level performance enhancement through a reduction of redundancy between subsystem materials and functions. To achieve this multifunctionality, additional elements must be embedded into the structure. The MFS design can incorporate electronics, thermal control, actuators and structural design into a single element. Thus, the feasibility of a MFS design depends on the internal and external interfacing capabilities and physical/chemical compatibility of the desired combination of subsystem functions [2]. Some main applications of MFS in composite aerospace systems are shown in Table 1. Thus, in order to maximize the benefits from a multifunctional composite structure, the system must be designed, analyzed, fabricated, and integrated by incorporating each distinct function relying on a concurrent design approach [3]. Therefore, it is clear that the MFS integration must begin early in the conceptual design phase of the system development for these payoffs to materialize [4].

Composite materials are ideally suited to achieve multifunctionality since the best features of different materials can be combined to form a new material that has a broad spectrum of desired properties. Nature's ultimate multifunctional composites are biological materials [5]. In fiber reinforced polymer composites, multifunctionality can be introduced through the reinforcement, the matrix, or with additional embedded elements. In the case of reinforcements, fibers can be made of carbon, glass, polymers, or metal, having special coatings to achieve different mechanical, electrical, chemical, and thermal properties. Also, the fibers can be hollow and then filled with special polymers for self healing capabilities [6]. From the matrix point of view, embedded particles in the polymer have proved to be very useful to increase electrical conductivity and for self-healing purposes [7]. However, the introduction of nanoparticles in the matrix, such as carbon nanotubes, offers new opportunities to incorporate a wide range of functionalities into future composite structures [8].

Until now, most of the multifunctional polymer composite applications have been limited to thermoset composites. However, thermoplastic composites (TPCs) are becoming more interesting for aerospace applications and they are moving quickly from secondary to primary structural applications. This relatively new but expensive material provides several processing and design advantages over thermoset composites. TPCs can be processed in a

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[*] AIAA member, g.f.ninomartinez@tudelft.nl
[†] Associate Professor.

few minutes while thermoset composites need a time-consuming cure cycle [9]. In addition, other benefits of thermoplastics are their toughness, chemical resistance, high temperature performance, indefinite shelf life (no refrigeration), low manufacturing costs, weldability, reshaping and reforming flexibility, better reparability potential and recyclability. A review of the state-of-the-art of thermoplastic composite technology in aerospace systems have been presented by Offringa [10].

Table 1. Some applications of multifunctional structures in aerospace systems.

Function	System
Structure-electronic	Aircraft [11, 12]
Structure-sensor	Satellite [13]
Structure-damping	Satellite [13]
Structure-electronic-thermal	Satellite [10, 13-15]
Structure-antenna	Aircraft [16]
Structure-battery	UAV [17] and satellite [18]
Structure-solar array	Satellite [18, 15]

The goal of this work is to increase the functions of composite aerospace structures using the fibers in stead of researching on emerging materials. Thus, a MFS concept for a leading edge that uses thermal active fabrics as internal heat sources based on metal fibers is presented. The metal fibers are embedded into TPCs providing an economical load bearing structure with ice protection system (IPS), enhanced non destructive inspection (NDI) capabilities for production and life service, and structural health monitoring capabilities. In addition, the metal fibers introduce electromagnetic properties into the composite for electromagnetic interference (EMI) and lightning strike protection. Finally from a design point of view, MFS offer the potential of high-level system integration with the electrical aircraft concept [19], increasing robustness, while reducing weight, assembly complexity, and manufacturing and operational costs.

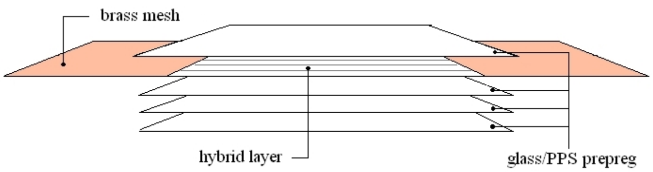


Figure 1. A schematic example of the hybrid lay-up using brass mesh bus bars.

II. Heat Emitting Layers for Multifunctionality

In this paper, the thermal active fabrics are called Heat Emitting Layers (HELs). A HEL is a hybrid fabric based on the same fiber reinforcement used in the composite but with a small fiber volume fraction of another kind of thermal or electrical conductive fibers. For example, glass fiber composites can use HELs based on glass fabrics with woven carbon or metal fibers. The HEL thermal activation is achieved by induction or electrical heating, which are based on eddy currents or Joule effect respectively. For electrical heating, busbars are used to distribute electrical currents through the HEL resistive fibers, and they are placed at the extremes of this ply. The concept is shown in Figure 1. Once the HEL has been activated, a heat front progresses through the thickness of the composite depending on the HEL position and desired functionality. From the heat transfer point of view, the process is described by the *heat diffusion* equation:

$$\nabla \cdot \kappa_i \nabla T \quad + \quad \dot{q} \quad = \quad \rho_i \, C_i \frac{\partial T}{\partial t} \quad \text{(Eq. 1)}$$

Where T is the temperature at time t, κ_i, ρ_i, and C_i are the thermal conductivity, density and specific heat capacity respectively for each material i inside the composite. The term $\dot{q}$ is an internal volumetric heat generation source and this power is generated by the HEL. On this work, the HELs were made of glass 8H satin fabric with interwoven 316 stainless steel fibers (70µm) at desired intervals. Metal fibers have been used as EMI shielding for polymers and fabric heating [20, 21]. The HEL and the busbars were placed as any other ply during conventional composite manufacturing. The functionalities introduce by the HELs are described in the following sections.

A. Ice Protection System

Since the beginning of aviation, icy conditions have been one of the major weather hazards encountered by aviators. In the right conditions, ice accretion on aircraft structures is an unavoidable occurrence both on the ground and in flight. Usually, ice forms on engine inlets and aerodynamic leading edge surfaces. At the lowest level of interference with the aircraft, ice causes lift and drag penalties thereby reducing aerodynamic efficiency [22]. At the highest level, severe ice accretion can lead to a change in flight dynamics, loss of control and ultimately to the aircraft crashing [23, 24]. With changing aerodynamic, engine designs, and economic and operation conditions, systems that have worked in the past, such as bleed air and pneumatic boots, do not fit with new highly efficient, highly streamlined composite aircraft structures. Therefore, new technologies based on “pipeless” electrothermal heaters are showing a huge potential for IPS, and they are being chosen for the next aircraft generation. Now, if the HEL concept is used as an IPS electrothermal heater; then, it can be incorporated into the reinforcement straightforward, i.e. the IPS can be integrated simultaneously during the composite structure manufacturing. This capability has the advantage that reduces time and the number of manufacturing steps. A set of 4-ply Glass/polyphenylene sulphide (PPS) composites with one embedded HEL, as shown in Figure 1, were manufactured to demonstrate the IPS capability. The specimens were placed inside of a small climate chamber (2) at -50^{o}C as illustrated in Figure 2. Water was poured on top of each panel to form an ice layer, and then, the HEL was activated with a power supply unit (5). The frozen and de-iced panels are shown also in Figure 2.

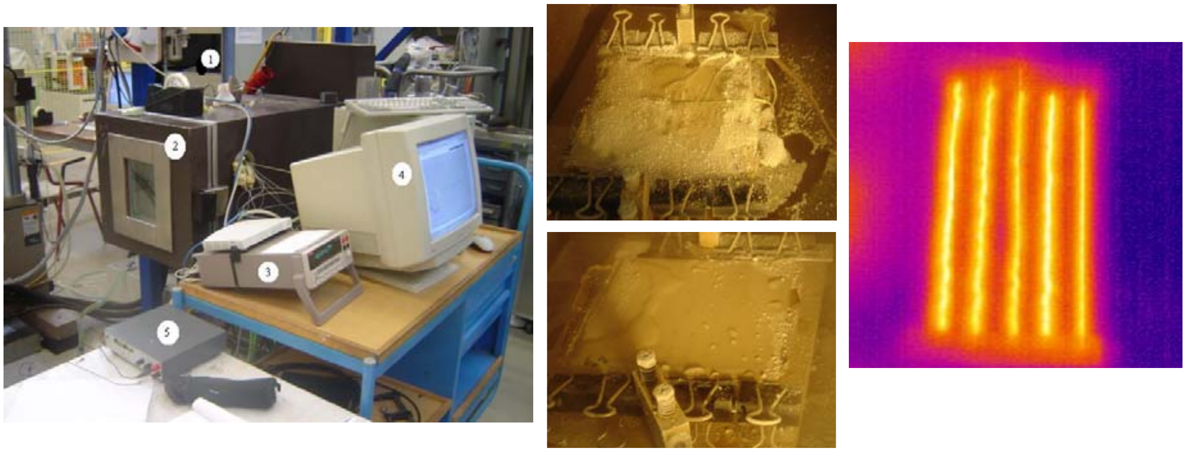
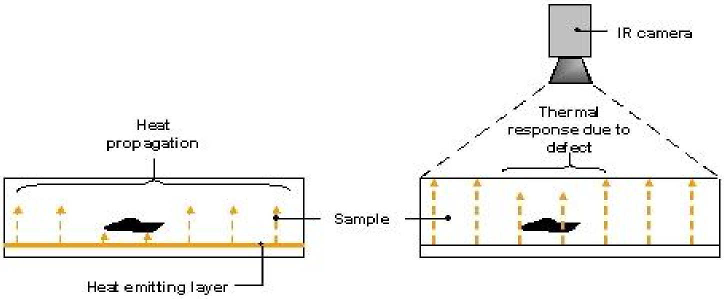


Figure 2. Climate chamber setup (left), panel with ice at -50^{o}C (top center), de-iced panel at -50^{o}C (bottom center), and infrared image of the HEL (right).

B. Enhance NDI and Health Monitoring

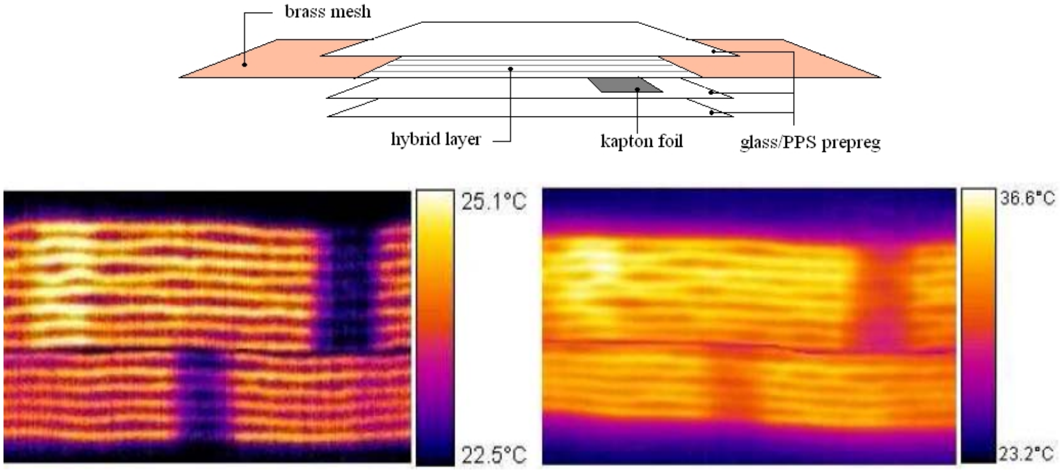
Composites are susceptible to damage but they are more difficult to inspect in comparison with metal structures. Defects may occur, and begin, beneath the surface undetectable to the naked eye. To meet the increase in composite usage, especially in high-performance applications such as aerospace, technologies must be developed to perform NDI on the structures such that they may be performed relatively quickly, and efficiently, during routine inspection. A number of NDI techniques are currently being researched and developed for assessing damage in composite laminates, such as thermography [25, 26], optical methods [27-29], electrical resistance methods [30-32] and acoustic emission [33]. Of these, infrared thermography is revealing its potential as a suitable NDI tool because through-the-thickness inspection is enabled simply through analyzing surface temperature changes. Although infrared thermography is already proving to be a useful method, composites do not behave as the ideal material for such analysis. Composites, and particularly unidirectionals, are anisotropic materials and as a consequence there is much noise associated with thermal images that are produced with thermography. The noise must be filtered out before proper analysis or distortion of information will result. Therefore, a simpler method to clearly detect and visualize defects in laminates utilizing the benefits of infrared thermography would obviously have a huge impact on the NDI procedure.



(i) t=0 (ii) t > 0

Figure 3. Non destructive inspection sketch of composites using the HEL concept. (i) Thermal activation of the HEL and interaction of the heat front with a fault, and (ii) Detection of the thermal response of the fault on the specimen surface.

In the MFS concept, the HEL is used to introduce a thermal signal inside the structure to improve the inspection of the system. For example, if a delamination is localized above the HEL, the heat front is delayed underneath due to the insulative effect of the air gap. This delay can be monitored as a temperature distribution on the surface using an infrared camera as illustrated in Figure 3. The idea of heating from within is that thicker and geometrically more complex shaped laminates may be investigated, because a uniform heat front can be created. As a demonstrator case, a 6-ply glass fabric/PPS laminate with three pieces of 125µm Kapton foils were used to simulate defects in the laminate. The HEL was placed in the 3rd ply and defects between 1st and 2nd ply, 3rd and 4th ply, and 5th and 6th ply. The thermal response of the laminate is shown in Figure 4. In the infrared images, the first defect (top left) looks brighter than the others due to the air gap thermal resistance limits the heat flow to the 1st ply. Defects 2 and 3 (center and right) appear darker because the heat flux from the HEL to the top is restricted by the air gaps. Further information of this technique has been presented by the authors in reference [34].



t=3s t =20s

Figure 4. Enhanced NDI of composites. Sketch of a laminate lay-up including the hybrid layer and a simulated defect made with Kapton foil (top). Thermal images of a composite sample with three embedded defects for 3s and 20s thermal activation times.

Finally, the electrical resistance of HEL network can be used for structural health monitoring and temperature sensing. Smooth variations on resistivity can provide the laminate temperature after a calibration process. On the other hand, an abrupt change on electrical resistance can indicate the presence of a fault or damage in the composite structure.

C. Improved Mechanical Properties -Erosion

Fiber reinforced polymer composite presents the realistic problem of erosion, these materials exhibit poor erosion resistance as compared to metallic materials [35]. Erosion has been defined as the effect of solid particles impinging a target surface causing local damage combined with material removal [36]. In aircraft, the most susceptible areas to be eroded are leading and trailing edges, radomes, landing gear doors, aerodynamic covers and fairings. This situation is particularly more critical during takeoff and landing due to sand erosion. However, these aircraft zones are made nowadays of composites. A standard practice to control the erosion is to bond a metallic strip on the most critical areas of the composite part.

In order to improve the erosion behavior in composites, our work has proved that it is beneficial to add a thicker layer of matrix at the surface of the laminate. The method utilizes a metal mesh placed on top of the lay-up. The mesh is composed of fine wires woven into an open plain weave which is embedded in the matrix. A comparison of the erosion performance for a laminate without metal mesh and one with a metal mesh is presented in Figure 5. With the aim to visualize erosion, the composite lay-up was made of three carbon/PPS and one glass/PPS woven fabrics. In the pictures can be observed that the metal mesh reduces considerable the erosion on the composite. The reason is that the mesh increases the local ductility of the upper surface while produces a rich matrix region, as result, erosion resistance is increased considerably. Therefore, the use of an embedded mesh in MFS, in comparison with a bonded metallic strip, is a weight-saving solution for erosion as the component density is reduced. As the mesh layer is placed on the surface, it provides an inherent lightning-strike protection for the system such as in aircraft and wind-turbine blades [37]. It is author's opinion that lightning protection in composites should not be considered as an additional function. It is just the minimum requirement to replace metals in aircraft structures. However, the added benefit of the metal mesh is that it offers a medium for rapid and efficient heat distribution over the MFS surface. This benefit is extremely important for an effective IPS application.

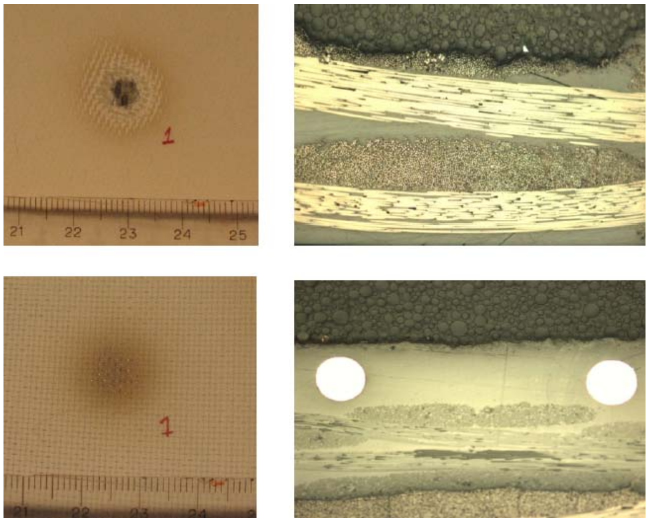


Figure 5. Eroded glass fabric/PPS laminates with rough sand impacted at 90^{o}. The images show the top eroded surfaces (left) and their cross-sections (right) for both a "plain" laminate (top) and one with an embedded metallic mesh (bottom).

III. Design Aspects for MFS based on HELs

A key step toward designing a multifunctional composite structure is to create a suitable model that adequately represents the MFS multiphysics nature, and operational and manufacturability conditions (requirements). A finite element (FE) modeling/analysis package can be used for this purpose. However, before such a model can be built, it is necessary to determine what level of detail makes a good comprise between accurately modeling the multifunctional structure and quickly obtaining results [12]. It is also important to evaluate the elements compatibility between the different involved physics.

A design scheme for the HEL based MFS is depicted in Figure 6. Once the composite configuration part is known and desired functions defined, the type of metal fiber can be chosen based on its properties such as electrical conductivity, chemical resistance properties, and manufacturability. For example, any kind of metal fiber can be embedded if the composite reinforcement is made of glass, but it is not the case with carbon, where electrochemical corrosion can be a serious problem. Then, initial environmental (boundary) conditions and power inputs are defined to start the process. Thus, using the maximum operating polymer temperature $T_{\max}$, functionality requirements and manufacturing considerations, the horizontal spacing between the metal fibers is chose. The process stops when the optimal conditions, given in function of environmental variables, power, and geometry, are satisfy for the different multifuntionalities involved in the design.

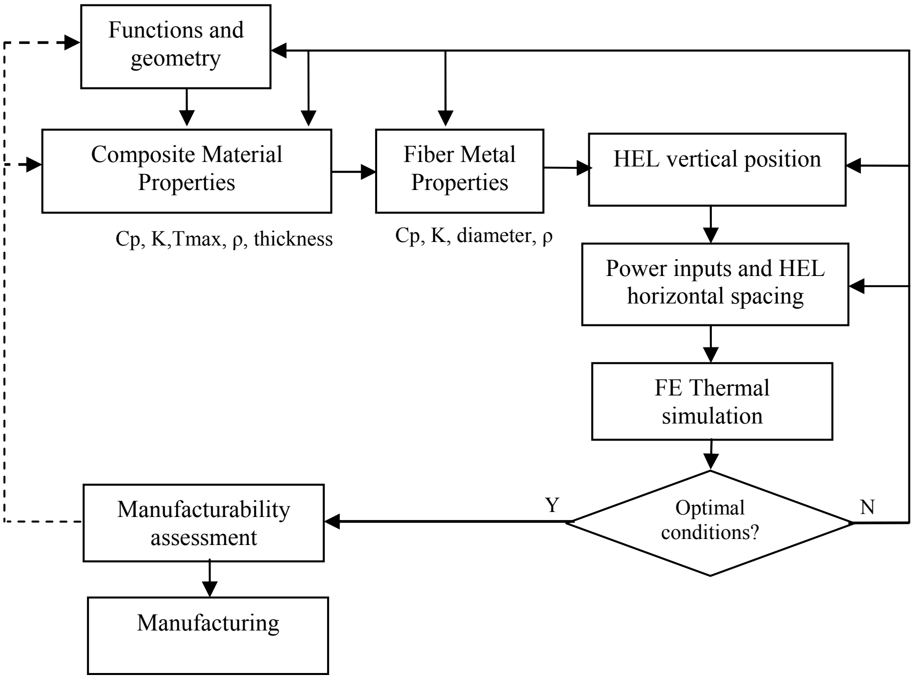


Figure 6. Design strategy for multifunctional composites based on HELs.

A. HEL configuration

The metal fibers can be placed within the laminate in three different ways: i) 1D interwoven metallic fibers, ii) 2D interwoven metallic fibers, and iii) cross ply interwoven metallic fibers, as shown in Figure 7. The surface temperature distribution depends on this fiber arrangement. If 1D metal fibers are used for example, the temperature profile has the form of a sine wave, then, the closer the fibers, the smaller the temperature difference between peaks and valleys, i.e. the better the temperature distribution over the surface. The use of a 2D fiber configuration introduces some electrical problems due to short-circuiting and subsequent uneven heating. Therefore, the 1D and cross ply metal fiber configurations are the most useful ones. From a practical point of view, it is important to ensure that all electric circuit paths, for the busbars and fibers remain closed through the life of the component. A critical limitation of embedded electrical conductors into composites is the mismatch in fatigue life. For instance, copper and aluminum typically exhibit significant lower fatigue life than fiber-reinforced polymer matrix composites. Thus for copper, if the stress is kept below 35% of its ultimate tensile stress, the copper will remain adequately conductive for twenty thousand cycles [11].

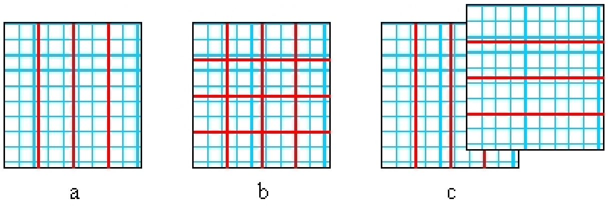


Figure 7. HEL configurations: a) 1D, b) 2D, and c) Cross ply. Bolder lines (red) represent the metal fibers.

B. Numerical Model

With the aim of finding optimal conditions for the MFS concept, several variables such as power input, horizontal separation *S*, vertical position *V*, fiber diameter *D*, delamination geometry *L*, heating time t_h, and environmental conditions were investigated using a thermal parametric finite element model. Figure 8 shows the model geometries for the IPS and NDI functionalities. In both cases, the simulation of the heat transfer (Eq. 1) through the laminate was performed using MATLAB coupled with COMSOL Multiphysics, a commercial FEA software, due to its ability to deal with multiphysics problems. The composite material was assumed homogeneous and orthotropic, and its properties were computed using the rule of mixtures with 60% fiber volume fraction as shown in Table 2.

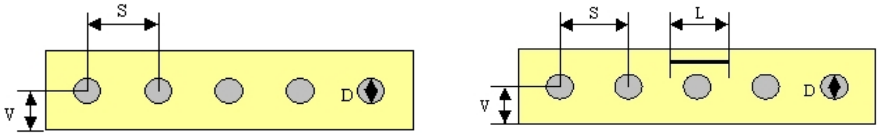


Figure 8. Thermal models geometries for IPS (left), and enhance NDI (right) functionalities.

Table 2. Material properties used on the FE thermal models.

Material	Kxx [W/mK]	Kyy [W/mK]	ρ [kg/m^3]	Cp [J/kgK]
Stainless Steel	10	10	7780	460
GF/PPS	0.722	0.722	2066	937.5
PI	0.25	0.25	1400	1200
Air	0.0257	0.0257	1.205	1005

IPS functionality: A 4-ply glass fabric/PPS was used to study the thermal response of an ice protection system. The laminate was modeled with one 1D HEL configuration and free convection conditions were assumed on both surfaces -50°C. The lateral boundaries were thermally insulated, in order to simulate thermal symmetry. Forced convection and ice melting processes were not included to simplify the model. In this way, a suitable temperature profile could be obtained through optimization of the fiber geometry and placement. Figure 9 shows an example of a solution generated with this model.

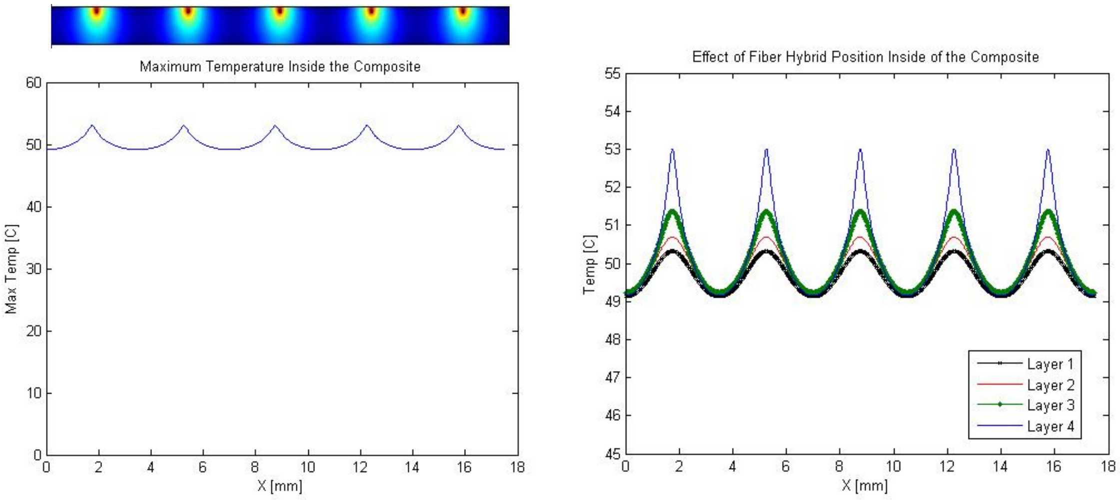


Figure 9. Typical thermal FE solution for 1D HEL configuration: Resulting surface temperature profile (left), and temperature profile in function of the hybrid layer position (right).

The effect of the HEL vertical position on the surface temperature profile is shown in Figure 9 too. As expected, the best place to place the hybrid layer for IPS is on the top ply, where the generated heat is transferred directly to melt the near-by ice layer. Regarding to the horizontal spacing, the best IPS is one which has the least difference in temperature between peaks and valleys. The shape of this profile is a function of the metal fiber horizontal spacing in the HEL: the closer the fibers the smoother the profile. However, the discrete nature of the woven fabrics, their manufacturability, and the maximum allowable temperature inside the laminate constraint the horizontal spacing. If the temperature around the metal fibers reaches $T_{\max}$, the mechanical properties of the laminate could be compromised. Therefore for each polymer matrix, the best horizontal spacing of the metal fibers with a given power input is such that the maximum temperature inside the laminate should be below $T_{\max}$.

NDI functionality: The NDI thermal response for a 6-ply glass fabric/PPS laminate with 1D HEL configuration was analyzed. The HEL had a fiber spacing, S, of 5 mm, and a step power input of 0.225 W/cm^2 was applied on the metal fibers. The laminate width was defined as 25 mm, and the delamination *L* was modeled as a polyimide (PI) insert of 5 mm length with a thickness of 125μm. Free convection conditions were applied in the top and lower surfaces with a convective heat transfer coefficient of 5W/m^{2}K and constant ambient temperature of 20^{o}C. The lateral boundaries were thermally insulated, in order to simulate thermal symmetry. For the NDI functionality, the delamination position with respect to the HEL affects the surface temperature profile as illustrated in Figure 10. In this Figure, a HEL was placed on the 6th ply with a delamination on top (cold spot) and one below (hot spot) of it. These numerical results are in agree with the experimental results shown in Figure 4.

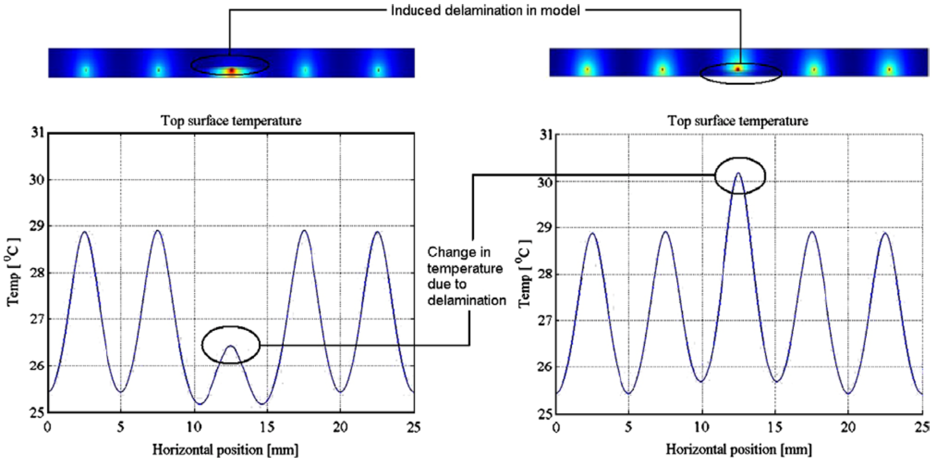


Figure 10. Typical thermal FE output for the NDI functionality with a HEL in the bottom ply: A defect above the HEL (left), and a defect below the HEL (right).

In order to analyze the data obtained from the FE simulations, two temperatures T_d and T_f were defined as the temperatures measured on the laminate surface above the defect and on a metal fiber respectively. The influence of the vertical HEL placement, *V*, on the difference in temperature (*DT*) between T_d and T_f for different defect positions can be observed in Figure 11. Three positions for the HEL were analyzed: top-ply, middle-ply and bottom-ply, and delaminations simulated at every layer, with the 1st at the bottom surface and the 5th closest to the upper surface. It is clear that *DT* is strongly related with the HEL and defect locations. The highest *DT* occurred when the HEL and defects were placed on the top-ply of the laminate; then, this value decreased quickly for deeper defects. When the HEL was placed in the bottom-ply, an even *DT* distribution was obtained for all defect locations. However, these values were smaller than 0.5^{o}C, because a considerable part of the applied power was transferred through the bottom surface to its surroundings. As result, a small heat flux was useful for detection. Finally, the placement of the HEL in the middle-ply produced a symmetric heat flux through the laminate and therefore higher *DT* values were found in general for all defects.

At this point, it is important to note the relevance of *DT*. This value provides a link between the thermal resolution of the infrared detector and the HEL. Thus, the probability of detection (POD) of a defect using a given hardware is proportional to *DT*, i.e. the smaller the *DT*, the lower the detection probability. A solution to improve the POD is to increase the HEL input power without degraded the polymeric matrix.

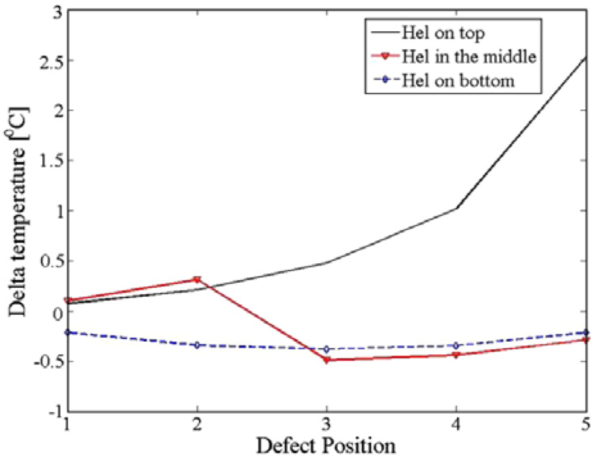


Figure 11. Influence of HEL position on the temperature difference measured at the composite surface with a power input of 1.72 W/cm^2 and 10s heating.

IV. Thermoplastic Composite Leading Edge

At Delft University of Technology, the rudder of an Eaglet aircraft, as shown in Figure 12, has been manufactured with a thermoplastic rudder formed by 3-ply (+-45/0-90/+-45) of CETEX Carbon/PEI [38]. The rudder is assembled using a resistance-welding process and most of the components have been thermoformed. The skin is manufactured from one single laminate folded with a hot wire, and the forward spar is a non uniform thickness flat laminate. The ribs were rubberformed, while both end caps were vacuum infused. From the manufacturing point of view, the leading edge is a single curvature element and its only fabrication concern is the mould geometrical correction needed to avoid spring-forward after thermoforming. Therefore, using the available tooling in-house, the Eaglet rudder's leading edge was selects as an application case of the MFS concept presented on this paper.

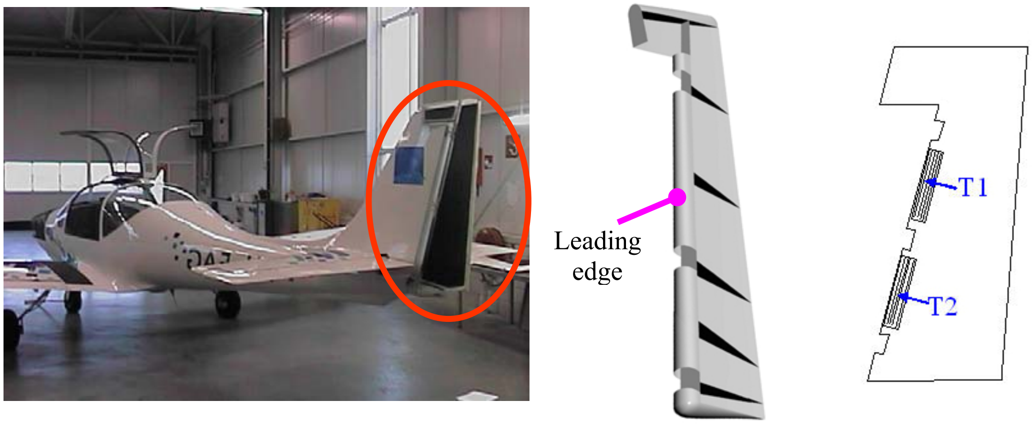


Figure 12. General aviation aircraft (left), its carbon/PEI thermoplastic composite rudder (center), and multifunctional rudder leading edge (right).

One of the main advantages of thermoforming technology is that it offers low manufacturing costs, however, it imposes higher loads on the MFS material such as maximum pressure and temperatures that the embedded elements must tolerate. Therefore, if the MFS survives this *rough and tough* manufacturing process, it will be also suitable for the same integration capabilities using a *soft* manufacturing technique such as RTM or vacuum infusion. In addition, thermoforming has a high potential as a manufacturing process for movable components in general aviation and unmanned aircraft vehicles.

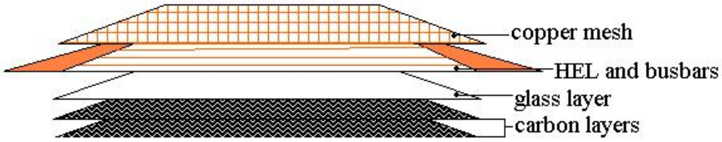


Figure 13. Laminate lay-up for the MFS leading edge.

The MFS rudder leading edge concept utilizes a HEL made of Satin 8H glass fabric with unidirectionally interwoven 316 stainless steel fibers placed on the top ply. Then, a metallic mesh to improve erosion has been placed on top of the laminate. An sketch of the laminate lay-up is shown in Figure13. First, two sections of the leading edge were manufactured in order to assess the integration and manufacturability of the IPS and NDI functions on this single curved product. The formed section and its infrared images for IPS and NDI are shown in Figure 14. The thermal pictures indicate that the HEL structure was not affected during thermoforming. In the case of the NDI, embedded PI pieces were used to simulate delaminations and they can be observed clearly on its infrared image on Figure 14 (right). It is expected that defect detection will be easier if an automatic process to stitch the metal fibers is used. On this paper, the fibers were woven manually and for that reason, the fibers do not look straight on the NDI image. Nevertheless, the HEL concept picks up properly the defect size and position.

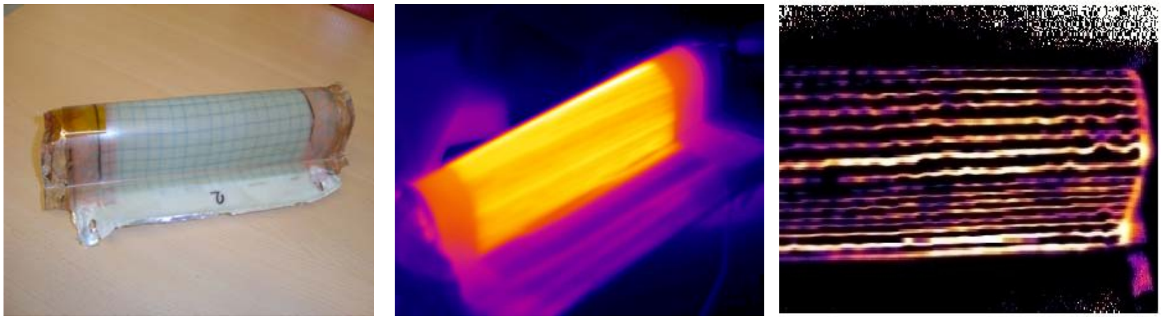


Figure 14. Rubberformed leading edge section: Formed leading edge part (left), thermal image of the IPS (center), Thermal image for NDI showing embedded defects (right).

Once the feasibility of the MFS leading edge concept was proved, a full scale MFS rudder leading edge was manufactured as shown in Figure 15. This leading edge has two heating sections as indicated in Figure 12. In order to produce this component, the HEL metal fibers were stitched on those zones and electrical connectors were placed trough the laminate build-up to provide power from the inside part of part. The laminate was consolidated and thermoformed in-house as it is depicted in Figure 15. Finally, the operational multifunctional leading edge is presented in Figure 16. Both IPS zones can be observed in the associated infrared picture.

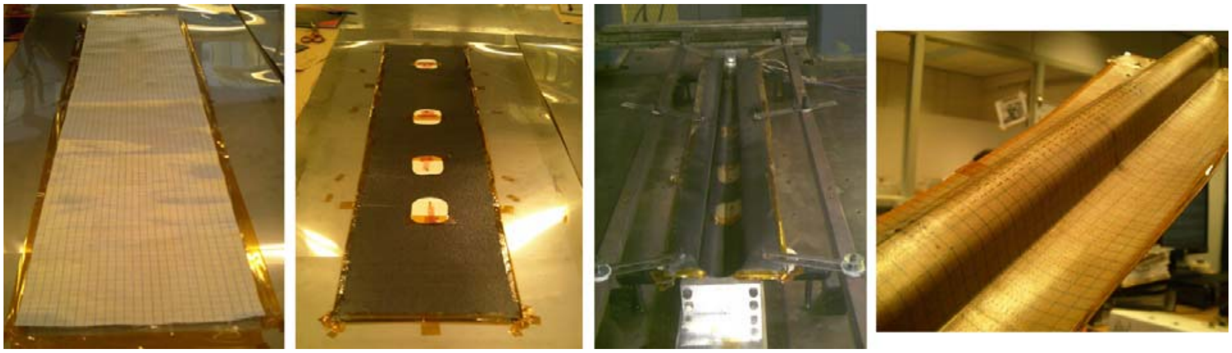


Figure 15. Rubberformed MFS leading edge: HEL (left), Carbon ply with electrical connectors (center left), Formed leading edge in the mold (center right), and untrimmed product (right).

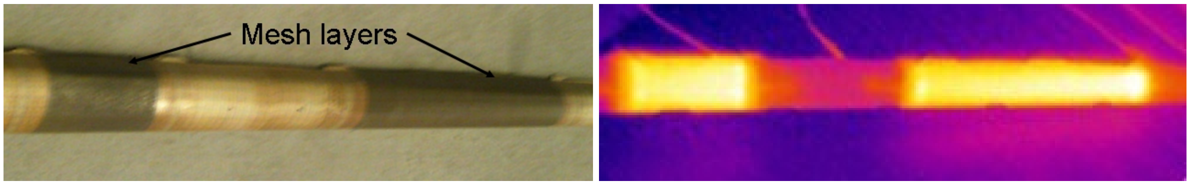


Figure 16. MFS leading edge of a general aviation rudder. Visual image (left) and its thermal image showing both IPS panels (right).

V. Conclusions

The use of heat emitting layers in composite structures has the potential to extend the functionalities of the component. This approach offers an integrated ice protection system, enhanced non destructive inspection, and improved erosion resistance among other functions. The main advantage of this integration relies on the reduced manufacturing steps involved and the lightweight of the system.

Designing a multifunctional composite system can be considered as a multidisciplinary design optimization problem but an intimate level, where the interactions between different physics are important. The different functions were first evaluated at laminate level, and then on real component parts showing that the concept is robust and reliable. The use of the rubber forming process has showed that heat emitting layer can survive this rough manufacturing process, which means that the concept is also suitable for the same integration using other manufacturing techniques like RTM or vacuum infusion. Therefore, the HEL based MFS concept can be used to extend current ice protection on all required composite aircraft surfaces beyond the typical leading edges.

Finally, the MFS concept presented on this paper offers the possibility to accelerate the implementation of MFS in current and future composite structures because it uses current certified aerospace materials and manufacturing process.

VI. References

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