Numerical and experimental validation of SMARt thermography for the inspection of wind blade composite laminate

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Abstract

An innovative active thermography technique is proposed for the inspection of typical wind blade material. The proposed technique is based on the use of a multifunctional material obtained adding a grid of Shape Memory Alloy wires, which would serve also as a protection against lightning, to a traditional glass fibre composite panel. This technique, called SMARt thermography, which exploits the SMA wires as internal heat sources, has been compared to a traditional pulsed thermography in the case of a representative panel of unidirectional glass fibre and epoxy matrix with embedded SMA wires and artificial defects. The experimental results of the two techniques are reported and compared to the result of a numerical FEM transient model, in order to establish the reliability and the detectability limit of the proposed technique. The FEM model has been proven to be a useful tool for the definition of the multifunctional material at a design stage.

Keywords Multifunctional materials · SMARt thermography · Shape memory alloy · Wind blades · Defect detection

1 Introduction

Wind energy exploitation is considered one of the most positive developments originated by today's storm of uncertainty unleashed as a result of turbulence on oil prices, climate changes, environmental degradation and dependence of foreign energy supplies. The success of wind energy is largely due to the fact that the cost of wind energy is comparable to the one of traditional fossil fuels, becoming attractive this form of renewable energy. However, research initiatives are aiming at increasing overall conversion efficiency, cost efficiency and significantly drive down the energy cost. In order to obtain lower rates of energy cost, larger wind turbines are commonly used. As a consequence of this trend, modern wind turbines are the largest rotating machines on Earth, with the length of one blade exceeding the entire span of an Airbus A380. These large turbines have been called "fatigue machines" and have design lifetime requirements 20 times longer

than standard cars. It is clear that design, manufacturing and in-service phases constitute critical issues and an additional effort is required for component optimization and structural integrity assessment.

The structural health of a wind turbine, therefore its operating life, is conditioned during its whole life by initial defects and defects arising after installation, when the wind turbine is exposed to environmental loading condition. Any difference of the real operating conditions with respect to those statistically estimated and used for design is a potential source of damage, possibly leading to a fault or to a reduction of lifetime. The development of techniques able to check the structural health of the wind turbines is very important, since early detection of possible structural defects potentially jeopardizing reliability of structural elements would inherently increase operating life-time and reduce the overall cost of energy. Several methods are available in industrial application and improvements of these techniques are continuously

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proposed. However, these techniques are often not directly applicable to the case of wind turbines, due to large size, difficult accessibility, need to monitor structural health on-site and sometime impossibility to disassembly the structure.

A central role is played by blades, whose improvement is crucial in terms of aerodynamic efficiency and of reliability and durability for the whole life-time (at least 20 years). Composite materials are widely diffused as a structural material. Their superiority is well established for all those applications requiring high stiffness/weight ratio. Using composite materials allows conceiving component as an assembly of laminate to obtain geometrical complex structures. The inherent high strength is enhanced by the possibility to optimize the layup in order to maximize the mechanical response for a given loading condition and minimizing the corresponding stress state. This fact gives an extraordinary freedom to designer that is simply unimaginable for homogeneous materials. Moreover, it is relatively easy to realize and assembly large structural components, justifying the extensive use of composite materials in various applications. As a result, composite materials are the only choice available for certain application. In particular, composite materials represent an ideal choice for the production of wind turbine blades, since these materials are characterized by highest compressive strength to weight ratio, stiffness to weight ratio and buckling stability. Considering exclusively these parameters, the best choice would be represented by unidirectional CFRP, but its excessive cost pushed manufacturers to use unidirectional GFRP. Therefore, wind blades are used to be realized with unidirectional composite laminate based on epoxy matrix and glass fibre. A typical content of 30–40% fibre volume content is considered for hand lay-up, arriving up to 50% using a vacuum bagging process [1].

Another advantage of composite material is related to the fact that even if the main function of a structural component is to sustain the applied load in the predicted environmental condition, it is possible that other secondary functions are required, which could depend by its specific ambit of use. Several examples could be the protection against corrosion or particularly aggressive environmental conditions, request of particular surface properties like wettability/impermeability, low friction, and specific thermal conductivity. Frequently, if the material itself does not have adequate additional properties, a certain number of strategies can be used, as for example the use of protective coatings, the execution of specific surface treatments and so on. The advantage of the composite material is that it is possible to obtain additional properties acting not only on the surface, like happens for homogeneous materials, but also on the bulk materials, adding for example to the matrix at a microscopic level additives like

particles of other materials, carbon nanotubes, metallic powder. Another possibility is to add a third macroscopic component to matrix and fibre that are characteristic of the composite material. This third additional component is represented for example by a different kind of fibre. The resulting material continues to be defined as a composite material from a structural point of view, but a definition of multifunctional material is more appropriate thanks to its capacity to absolve to several functions.

The development of multifunctional materials is an important challenge, since a multi-objective optimization of the material could be reached, giving potential advantages for a large number of applications. This challenge requires a high research effort primarily concerning the manufacturing point of view and secondly the design and testing of these innovative materials.

The variety of multifunctional materials that have been proposed is very vast [2, 3] and others will be proposed in the future. Mechanical behaviour of multifunctional materials and structures for general purpose applications [4] or aeronautical structures [5] can be easily founded in literature. However, a particular category is obtained by embedding a grid of metallic wires in the composite structure. The hybrid metal/carbon fibre or metal/glass fibre composite is generally characterized by high mechanical properties and improved impact strength. Additionally, they can enhance the possibility to detect inherent or load induced damage, allowing the strain sensing or finally acting as thermal heat sources for de-icing in the aeronautical field [6]. The introduction of metallic wires is useful also to improve the electromagnetic shielding and protection against lightening and electrical discharge for wind blades.

A promising application of this kind of multifunctional material has been considered in this work and concerns the manufacturing of wind blades. The use of a multifunction composite material, obtaining simply adding metallic wires to a standard unidirectional GFRP, could lead to several advantages, in term of reducing the probability of wind blade failure during service. At this purpose, these advantages are justified examining the most common failure causes. A statistical examination of blade failures is reported in [7]. Neglecting the case of failures originated by variability and exceptionality of load conditions, a relevant failure probability is associated to the presence of defects, which lead to a progressive mechanical degradation and loss of structural capacity of the blade. Defect can be introduced during manufacturing process or during service, as a result of bird-strike impacts or crane impact during maintenance. This justifies the importance to assure a high quality level during manufacturing and the need to use appropriate non-destructive techniques for the

assessment of the blade structural integrity, not only before installation but also during in-service operation or after localized repairs. Another important cause of failure is recognized as the lightning damages. Generally speaking, points where lightning discharges are close to the blade end [8]. The formation of electric arcs interior to blade and between different layers of composite laminate originates transitory pressure waves that can lead to micro-crack nucleation on the blade surface and in the more severe case the complete disruption of the blade. In order to limit the damage, it is important to allow an ordinate transmission of the electric current on the external surface of the blade to the metallic nacelle avoiding the formation of electric arcs. One possibility is to fix electric wires on the surface, even if a decay of the aerodynamic properties of the blade is obtained. The best solution is to add a metallic net internal to the blade surface.

In both cases, the use of a multifunctional material could potentially lead to reduction of lightning damages and increase of the structural integrity assessment through an improvement of defect detectability in large structures like wind blades. To understand how it is possible to improve defect detectability adding metallic wires in the composite used for wind blade manufacturing, it is necessary to argue about the techniques used for non-destructive evaluation and the problems encountered in the examination of large structures as wind blades.

The most common techniques used for the non-destructive evaluation of wind blades are ultrasound and thermographic technique. The first one is more sensitive and allows detecting with high precision defects having low dimensions, but requires a long examination due to the large dimension of the wind blade. This process can be automatized, but only at the end of the manufacturing process. It is unimaginable to carry out an ultrasonic inspection during scheduled blade maintenance without forecasting the dismounting of the blade from the nacelle. The second possibility is to use thermography, which is a non-contact and long distance non-destructive technique. Thermography is useful for inspection of wide areas; therefore it could be possible to carry out the inspection without removing blades during service. The work of Maldague [9] represents the starting point for several thermographic techniques that have been developed for control purposes. The thermographic technique could be passive, that is without application of an external heat source but simply observing the environmental decay of temperature, or active, in which a heat source is used to enhance the thermal phenomena. Although active thermography is more suitable for defect detection, use of external heat sources for the inspection of wind blades could be very difficult;

therefore the common adopted solution is to use passive thermography, even with the known limitations [10].

Starting from these considerations, it is clear that introducing metallic wires into the structure of the composite laminate is potentially interesting also at the purposes of thermographic assessment, since it is possible to use metallic wires as internal heat sources simply applying an electric current. In this manner, a double advantage could be reached, justifying the complication and the higher cost of the material: the problems of damages induced by lightning could be solved in an excellent way and it would be possible to use an active thermography technique for the non-destructive evaluation of the blade during service. However, the potentiality to use this kind of multifunctional material for structural integrity assessment of blade requires be studying and comparing with traditional active thermography, in order to evaluate if the technique has a comparable sensitivity of traditional active thermography. Having in mind all these considerations, the aim of this work is to study the potentiality of this technique in view of an application to the control of wind blades.

For a better reading and comprehension of the work, the paper has been structured as in the following. After the introduction considerations, Sect. 2 of the paper starts with a description of the SMARt thermography technique, in which the technique is regarded as an evolution of different proposal of other researchers and related to previous experience of authors. The section continues with the presentation of the case study, the description of the thermographic set-up that has been adopted and the definition of the procedure followed for the experimental data elaboration. Section 3 is devoted to the numerical analysis, presenting the geometric details of the model, the physical properties of the materials involved and its validation through comparison with experimental results. Section 4 illustrates and discusses the main results separately for traditional and SMARt thermography. Finally, the main results are recalled in the conclusion.

2 Smart thermography

The experience matured in other industrial sectors, as the aeronautical one, has been considered the starting point for the application presented here. In recent years, a particular multifunctional material has been proposed [11–13], which is realized embedding Shape Memory Alloy (SMA) wires in traditional carbon or glass fibre reinforced composite laminates. The introduction of SMA wires in composite acts as a secondary reinforcement for the composite, determining an increase of the impact resistance, thanks to the possibility of dissipating energy during the martensitic phase transformation that this kind of material

suffer when subjected to plastic deformations. Moreover, a grid of SMA wires inserted in the composite is capable to constitute an internal heat source, if an opportune electrical current is applied. This internal and diffused heat source can be useful for several applications, as for example for de-icing, strain sensing and damage detection in the aeronautical field. It is also possible to use it for simplifying the application of non-destructive technique based on active thermography.

Technical literature about composite material enhanced with the insertion of SMA wires is relatively limited. A resume of the mechanical properties improvements that can be obtained is reported by Angioni et al. [12]. Other applications consist in the use of SMA wires as strain sensing integrated in the composite: in this case the damage progress determined by impact or relevant load could be easily monitored [14–16]. However, the first idea to introduce a heat source layer embedded in a composite laminate for non-destructive control purposes was successfully exploited in [17], even if the solution was excessively invasive with respect to the mechanical behaviour of the material. Also the insertion of 3D electrical circuit in the composite [18] could potentially lead to a worsening of the mechanical properties of the material, which is unacceptable for several applications. A simpler and less invasive solution has been proposed by Pinto et al. [13] and successively by Angioni et al. [11]. In this case, a simple grid of SMA wires is inserted between two plies and the influence of various parameters on the detecting possibility has been considered. The comparison of the traditional active thermography with the respect to the introduction of diffused internal heat sources is graphically represented in Fig. 1.

The idea to use this technique for the monitoring of large structural components link wind blades is supported by the experience of other researchers working on this specific field. Active and passive thermography were used

for the control of a portion of a damaged wind blade [10] and this paper witnesses the difficulty to examine a large structural component, in this case a portion of a large wind blade, using an active technique. The control on large part is possible only using passive thermography but you need to carry out the inspection outdoors in a sunny day from morning to evening [19]. As a consequence it would be very complicate or impossible to carry out the inspection in winter or with different wheatear conditions. Several examples of inspections made on installed wind blades are reported in [20, 21], but the difficulties of the measurements during on site measurements are clearly highlighted. Other example, which includes thermographic flight inspection using unmanned vehicles, are reported by Galleguillos et al. [22], which used passive techniques.

This not-exhaustive collection of papers highlights that the inspection of in-service wind blades is very complicated and passive techniques are generally adopted. As a consequence the possibility to use an internal heat source for applying an active thermographic technique would be very attractive, especially for in-service controls. SMARt thermography allow simplifying considerably the inspection technique, since it is possible to obtain a quite uniform heating of the components without particular difficulties, as showed numerically and experimentally by authors [23]. However, the practical application of SMARt thermography to the control of industrial components presupposes the determination of the applicability limit and the evaluation of the reliability of the technique. In this preliminary work a representative component made of unidirectional glass fibre has been considered introducing known artificial defects having different dimensions and localizations and try to individuate it. The defects have been individuated both using a traditional active thermography, using the halogen lamp for heating, and SMARt thermography, exploiting the internal sources represented by SMA

Fig. 1 Schematics of traditional active thermography **(a)** and material enabled thermography **(b)** [24]

wires. This comparison with a well-established inspection technique like conventional pulsed thermography was conceived to establish in a general way the limits of applicability of SMARt thermography, rather than a direct comparison of the two techniques for the specific inspection of wind blades. In other words, only a direct comparison of SMARt thermography to the usual passive techniques adopted for the control of wind blades could establish a superiority of one technique with respect to the other. This aim, however, is beyond the scopes of the present work, which must be considered an assessment in laboratory conditions of a technique that prospectively could be applied for wind blade inspection.

The experimental evaluation of defects through traditional active thermography and SMARt thermography has been combined with the FEM numerical simulations of the two techniques. The numerical model has been used to establish the limit of detectability with the two techniques and to establish the correct level of heat source needed to obtain a correct evaluation of defects. This tool would be fundamental in the case of application of SMARt thermography for real structural component, where one parameter to establish is the amount

of current to be used to reveal a minimum dimension of defects.

2.1 Case study

A flat GFRP laminate panel constituted by 8 unidirectional plies has been realized by hand lay-up process (Fig. 2a), obtaining a fibre volume fraction of about 55%. Fibre was available in unidirectional coils with a density of 600 kg/m², while matrix is realized using a commercial epoxy resin. Fibre and matrix reference and main properties are reported in Table 1. In particular the panel has dimension of 210 × 210 mm and an overall thickness of about 8 mm. The panel contains one grid of SMA wires made of Flexinol® having a diameter of 0.25 mm; the grid is localized between 1st and 2nd plies. An array of 8 defects is inserted at various locations and depth inside the panel. The defects d1, d3, d5 and d7 are located between the 6th and 7th layers, while the defects d2, d4, d6 and d8 are located between the 4th and 5th layers. All the defects are approximatively located in the middle of the grid of SMA wires, which is the worst condition for the detectability of the defect [13]. As the defects act as a shield for the thermal output

Fig. 2 Realization of panel with embedded SMA wires and defects: **a** details during manufacturing phases; **b** geometry and localization of defects

Table 1 Mechanical and physical properties of glass fibre and epoxy resin

E-glass fibre—Selcom Multiaxial Technology srl	
Mean diameter [μm]	14
Density [kg/m^3]	600
Young modulus [MPa]	72,500
Ultimate stress [MPa]	2150
Ultimate strain [%]	3.75
Epoxy resin EC 130 LV + hardener W340—Altana Varnish Compounds	
Density [g/ml]	1.14/1.16
Young Modulus [MPa]	2900/3100
Ultimate stress (MPa)	75/80
Ultimate strain (%)	8.5/9

Table 2 Detail of defects introduced in the panel

Defect	Diameter d (mm)	Depth h (mm)
d1	25	3
d2	25	4.5
d3	15	3
d4	15	4.5
d5	10	3
d6	10	4.5
d7	5	3
d8	5	4.5

of wires, this shielding effect is minimized if defects are away from the heat source. Defects have been realized with polystyrene and then inserted between the layers during the manufacturing process. The geometry of the panel and the localization of the artificial defects under study are reported in Fig. 2, while Table 2 resumed the main geometrical parameters of each defect.

2.2 Thermographic set-up

All the thermographic inspections of the panel were carried out with the technique of the pulsed thermography, using a FLIR 7500 M IR camera with a FPA (Focal Plan Array) cooled detector, endowed with a NETD (Noise Equivalent Temperature Difference) of 25 mK, InSb sensor and image resolution 320×256 pixels. The distance between specimen and the infrared camera was optimized at 730 mm.

First of all, the traditional heat source constituted by halogen lamps was used. Four halogen lamps, differently oriented and controlled by a function generator, were connected to a Dimmer power source for synchronizing time between the thermal pulse and the recording initialization. IR camera and the heat source were localized on the same side (Fig. 3a).

In a second time the approach proposed as SMART thermography was used. In this case the heat source is represented by a direct current generator, simplifying remarkably the experimental set-up and time needed to obtain

Fig. 3 Thermographic set-up: **a** traditional thermography and **b** SMART thermography

a good quality of measurements (Fig. 3b). In this case, in fact, the uniformity of the heating over the panel surface is inherent to the technique and does not require a meticulous and boring improvement of the lamp orientation.

Adopting the set-up of Fig. 3, two tests were performed using the traditional pulsed thermography varying the heating time t_h from 3 to 10 s and observation time t_{obs} from 150 to 400 s respectively. Further two tests were carried out using SMARt thermography. The panel was disposed in manner that defects are comprised between SMA wires and IR camera, acting a transmission setup, which is the only configuration capable to produce meaningful and measurable alteration of the thermal field [6, 24]. An electrical power of 11.7 W was applied that corresponds to the electrical voltage and current reported in Table 3. Preliminary tests were carried out using lower electrical power, but this leads to unacceptable low temperature variations that inhibits the possibility of defect detection. Considering the limited amount of heat power that characterizes SMARt thermography, a sufficient amount of energy is reached considering duration of heating varying between 120 and 240 s (Table 3). The limited amount of the power that is possible to use in SMARt thermography would constitute a critical point in the defect detection capability, as discussed in the result session. An increase of it would be desirable, considering that the limitation of heat power due to the transition phase of SMA and the possible degradation of epoxy resin (about 70 °C) is adequately far from the experimental ones.

2.3 Data elaboration

Thermography uses thermal contrast as a basic parameter for the localization of defects. The surface temperature contrast is therefore used to investigate the defect detectability, using pulsed transient thermography [25]. A Matlab algorithm that has been previously developed by authors [26] has been used to upload the 3-dimensional matrix of thermal frames and to return selected thermal maps of specimen for various tests, detecting in particular various heat accumulation zones obtained over time, between intact and damaged areas [27]. The basic principles of this algorithm are here recalled in the following to

describe the procedure adopted for the data elaboration. The absolute C_a and normalized C_n contrast are defined by the Eqs. (1) and (2):

$$C_a(t) = T_{DZ}(t) - T_{IZ}(t) \quad (1)$$

$$C_n(t) = \left(\frac{T_{DZ}(t)}{T_{DZ}(t_0 + 1)} \right) - \left(\frac{T_{IZ}(t)}{T_{IZ}(t_0 + 1)} \right) \quad (2)$$

The temperature used in these formulas is the mean temperature in the reference area associated to the defective (DZ) and intact (IZ) zones at a given time (t) during the cooling transient phase and $(t_0 + 1)$ is the temperature immediately after the end of the heating phase. Absolute contrast method has limitations due to the adopted set-up and the operator choice of ideal areas for the contrast computation test. Therefore, the main drawback of classical thermal contrast analysis is establishing an arbitrary intact zone for each selected defect. Since ideal condition for thermal contrast calculation is verified when the sound zone is invested by the same heat flux of the defect zone, this calculation depends on the choice of the reference zone. The method used for selecting a free-defects portion of the specimen that presumably receives the same thermal flow of the corresponding damaged area is the Source Distribution Image (SDI) [28]. Thermal contrast of each defect is averaged using five different arbitrary intact zones, in order to reduce further the influence of the operator choice. The thermograms analysis at the beginning of the cooling phase for the PT tests 3 s and 10 s allow estimating the heat distribution quality in terms of its uniformity (Fig. 4), as well as the presence or absence of pre-accumulation of heat in the defective areas. The analysis of the isotherms from cooling thermograms shows the non-uniformity of heat deposition on the plate; the used C_a and C_n algorithm takes into account the SDI method during the selection of the intact points, corresponding to the previously determined defective regions. Based on the principle of equal excitation energy, the SDI approach should minimize errors in thermal contrasts evaluation. A heating time of 3 s is found to be sufficient to detect defects. Some degree of heat accumulation is revealed

Table 3 Main parameters used for traditional and SMARt thermography

	No. Test	ΔV (V)	I (A)	t_h (s)	t_{obs} (s)	frame rate (Hz)
Traditional thermography	1	–	–	3	150	5
	2	–	–	10	400	5
SMARt Thermography	3	30	0.39	240	1200	5
	4	30	0.39	120	1000	5

Fig. 4 Maps of isotherms on the panel surface at the beginning of the cooling phase for the traditional thermography, using heating times of 3 s **(a)** and 10 s **(b)**

during heating phase in the test of 10 s, due to marginal defects depth.

Comparing thermograms during the cooling phase for traditional and SMART thermography (Fig. 5), it is possible to observe a more uniform distribution of thermal energy in the SMART test, in terms of temperature differences between the different areas of the panel surface. It is evident the high uniformity of the thermal map that characterizes the SMART technique and, on the other hand, the limited differences existing in the temperature between defect and intact zones.

After choosing a thermal frame where the defects are more distinguishable, the algorithm provides an interactive analysis procedure for selected defective and intact zones section. This procedure is automatically iterated

many times for all defects, in order to characterize them. From the acquired temperatures in the selected areas, another Matlab routine calculates the diagram against time of absolute C_a and normalized contrasts C_n , as defined by the Eqs. (1) and (2). These diagrams allow the characterization and the comparison between the various damaged zones.

However, the determination of the thermal contrast following this procedure could potentially introduce a certain degree of error. The first critical point is the need to choose arbitrarily a reference non-defective zone for each defect, which causes an undesirable dependence of the thermal contrast from the choice of the intact and defective zone. Another limitation is that the analysis is done at the local level and undergoes preliminary choices of the

Fig. 5 Map of isotherms in the cooling phase **(a)** for the traditional thermography (heating for 3 s) and **(b)** SMART thermography (heating for 240 s)

operator on thermograms. Sometimes, the heat quantity deposited by the external source is not uniform, therefore different zones have different cooling temperatures and gradients and different defects can be misjudged as identical. Moreover, a single defect at a time can be analysed. In order to overcome these difficulties and to enhance the better individuation of defects, a new contrast algorithm has been proposed by authors [24, 26], that automates the detection and mapping simultaneously of the local contrast to identify defect boundaries onto the whole surface. In other words, the local contrast is automatically determined investigating the zone with highest temperature in pre-defined areas. This procedure overcomes the need to individuate the defect and integer zones, choice which is subjected to the personal evaluation of the operator. For each pixel of the thermographic image, new Matlab procedures rework the differences of the reference temperatures determined in the two-dimensional array of pixels near the calculation point pixel by pixel of the thermogram. This algorithm is based on the principle for which the reference temperatures evaluated around the chosen inspected spot tend to reach similar values when overpass the defect border, leading to small Local Contrast variations whose values are displayed with zero edges on contrast maps, clearly distinguishing the damaged zones and defect shape. The iterative calculations for all pixels on specimen allow achieving defect representation for the whole specimen (Fig. 6).

3 Numerical simulation

A numerical model of the thermal transient and steady state of the panel has been built in order to evaluate the detectability of defects with the two techniques. In particular the first model simulated the traditional thermography: in this case the heat source is applied as a uniform temperature over the surface of the plate, simulating the fact that at the end of the heating phase with the halogen lamp, the temperature of all the point of the surface is the same. This is obviously a strong hypothesis, which is not verified in the practice. Nevertheless, in this manner it has been possible to update the model comparing the numerical and experimental results in order to establish in a simple and efficaciously way the best combination of thermal parameter of composite for a good correlation of numerical and experimental data. Thanks to this updating phase, the model has then been used to forecast the thermal behaviour of the panel using the internal heat source of SMA wires. The idea is to use this model as a tool to establish the better combination of parameters for the detection of defects having a fixed minimum dimension. The comparison of numerical prediction and experimental data of SMART thermography reached the same level of the starting model, confirming its validity also for thermal loading conditions that are significantly different.

3.1 Description and generation of the model

The three-dimensional geometric model of the panel, comprehensive of SMA wires and defects, was built using CATIA V5 software in order to reproduce the panel having dimension $210 \times 210 \times 8$ mm used for

Fig. 6 Contrast map for defects detection in **a** traditional thermography (heating for 3 s) and **b** SMART thermography (heating for 240 s)

Fig. 7 Geometrical model generation with insertion of SMA wires and artificial defects between the 4th and 5th layers and between the 6th and 7th layers

the experimental evaluation. The model was obtained assembling 8 volumes having the thickness of 1 mm, corresponding to the one of a single layer. The first two layers were modelled simultaneously to include the 0.25 mm diameter SMA wires between 1st and 2nd layers. Defects are defined as surface entities in the Generative Shape Design. In this manner the defects are simulated as regions, corresponding to the modelled surfaces, where the nodes are disjointed. All the parts are finally assembled (Fig. 7), saved in STEP format and subsequently imported into Salome-Meca using the Geometry module. The model was discretized imposing a mapped configuration and adopting hexahedral elements HEXA8 in the Mesh module of Salome-Meca. The final model consisted of 247,783 nodes and 1,075,360

elements, able to define correctly the geometrical detail around the SMA wires (Fig. 8).

3.2 Material properties and tuning of the model

A transient thermal analysis was performed using the open source FEM software Code-Aster. The thermal properties to be assigned to the material for a transient linear analysis were the thermal conductivity k [W/(mK)] and the volumetric thermal capacity C [J/(m³K)].

Thermal conductivity of a fibre-reinforced polymer depends on the fibre type, orientation, fibre volume fraction and lamination configuration. For unidirectional 0° composites, the longitudinal thermal conductivity is controlled by the fibres, while the transverse thermal conductivity is controlled by the matrix [29]. The composite material was considered homogeneous but characterized by thermal orthotropic properties. The values of the thermal conductivity and specific heat have been assumed on the basis of literature data [30] for fibres and matrix and on the basis of technical sheets for SMA wires [31, 32]. The thermal properties used as input are reported in Table 4.

Another important parameter to be settled is represented by the heat convection coefficient h , which is required to describe the thermal exchange of heat with the surrounding environment. Due to the low difference of temperature between panel and air, the relatively low amount of data of polymers and the high thermal insulation of these materials with respect to metals, this parameter is difficult to be estimated using simplified empirical

Fig. 8 Mesh of entire panel (a) and a detail of the wire mesh (b)

Table 4 Thermal properties of materials

Thermal properties		Composite Laminate	SMA wires
kl—Thermal conductivity—longitudinal direction	[W/(mK)]	1.3	18
kt—Thermal conductivity—transversal direction	[W/(mK)]	0.21	—
C—volumetric thermal capacity	[J/(m ³ K)]	550,000	5,400,000

formulas reported in literature [33]. For this reason, a preliminary tuning of the model was needed. Using as reference the experimental curve temperature against time in the central area of the panel, h was varied between 2 and 10 [W/(m² K)] up to obtain a quite good superposition of numerical and experimental heating–cooling curves. The tuning procedure, simulating the panel heating through external heat source and the following cooling, provides the correct value for h coefficient equal to 9.2 [W/(m² K)]. This value is in good agreement with the value reported in similar works [34–36]. Moreover, the thermal output of the numerical simulation is quite insensitive to uncertainties of composite thermal parameters, since the introduction of a $\pm 10\%$ variation of volumetric thermal capacity C and convective coefficient h produces a negligible variation (± 0.2 °C) of the maximum temperature at the end of the heating phase. This observation is relevant in order to consider the numerical model a tool to be used preliminary to plan a thermographic inspection on a full-scale component.

3.3 Generation of numerical thermal images

In the case of traditional thermography, the thermal load was obtained imposing a uniform temperature of 29.14 °C on the nodes on the top panel surface, corresponding to the maximum temperature achieved in the experimental test after a heating time of 3 s. The heating phase was followed by the cooling phase for duration of 150 s. This assumption of the heat source, derived from empirical observation, is very simple and avoids complicating the need of a tuning of the heat source parameter. It has the disadvantage to do not consider the lack of uniformity of the heating source, but this is difficulty modelling also with more complicate approaches [35, 36].

In the case of SMARt thermography simulation and on the basis of previous work [23], the transient thermal analysis was performed applying the thermal load as the power density (power for volume unit) on the SMA wires. As an electrical power of 11.7 W was used in the experimental test, corresponding to the electrical voltage and current reported in Table 3, the applied power density was equal to $39 \cdot 10^6$ W/m³. This thermal load was supplied for the duration of heating time t_h , whilst the analysis was prolonged up to the whole observation time t_{obs} to simulate the cooling phase.

For both models, the initial temperature of the entire model was imposed equal to 22 °C.

As a result, the thermal map on the model surface during the heating and cooling phase was stored as text file containing the data of digital thermal images. The structure of this text file is composed by the nodes coordinates and temperature values for each instant and

was conceived to be identical to thermograms data files obtained by experimental measurement. In this manner, these file are therefore suitable to be elaborated with the same Matlab algorithms used for experimental maps.

The experimental and numerical thermal maps on the panel surface are showed in Fig. 9 for traditional (a–b) after 22.2 s from the end of heating time t_h of 3 s and SMARt thermography (c–d) after 468.8 s from the end of heating time t_h of 240 s. It is interesting to note that the numerical model of the SMARt thermography suggests the undetectability of the smaller defects d7 and d8, which are on the contrary visible on the traditional set-up, as confirmed by the experimental measurements. These observations confirm the validity of the numerical model as a tool for predicting the maximum dimension of the visible defect prior to execute an experimental measurement and as a powerful tool for the planning of inspections. Moreover, the consideration that can be derived is that the smaller defects could be visible also with SMARt thermography increasing the supplied heat source.

Numerical models allow calculating also the absolute contrast that can be obtained by the two techniques with respect to the visible defects. The examples reported in Fig. 10 show the comparison of numerical and experimental absolute contrast evaluation for two representative defects. Numerical behaviour is clearly not affected by noise. The numerical contrast curves qualitatively agree with the experimental ones, while the quantitative evaluation is not always acceptable.

4 Results and discussion

The experimental data obtained by the thermographic inspection have been elaborated using the numerical procedure presented before. In particular both for traditional and SMARt thermography, the thermal maps were elaborated to individuate defect and intact zones.

4.1 Traditional thermography

Figure 11 reports the thermograms that have been used to calculate absolute and relative contrast according to SDI method for the two heating times that have been considered. These thermograms have been selected on the basis of the best achieved defect visualization, respectively for the test with heating time of 3 s and 10 s. Analysing the thermal map, the first observation is that traditional thermography is able to find all the defects inserted in the panel, in particular defect d7 and d8 that are characterized by the minimum diameter of 5 mm, according to the prediction of the numerical model.

Fig. 9 Comparison of experimental and numerical thermal maps: experimental (a) and numerical (b) traditional thermography after 22.2 s from the end of heating time t_h of 3 s; experimental (c) and

numerical (d) SMART thermography after 468.8 s from the end of heating time t_h of 240 s

The trends of absolute and normalized contrast over the whole observation time are reported in Fig. 12 and 13 for the two considered heating times. Independently from the heating time, the trend of the absolute contrasts appears quite regular for all the defects, even if some noise appears for defects having the lowest values of absolute contrast (Fig. 12a, 13a). The values are quite similar for all the defects that have the same depth, with the exception of defect d7. In the case of heating time of 10 s, absolute contrasts are higher, but a pre-accumulation of heat during the heating phase was observed. This circumstance is also showed by the fact that the curves of the normalized contrast in the case of a heating time of 10 s show a discontinuity in its first derivative (Fig. 13b). The data obtained by these curves are synthetically resumed by the maximum values of the

contrast (Table 5), which are reached at a certain time after the end of the heating phase.

4.2 SMART thermography

In the case of the SMART thermography, the acquired raw data, corresponding to the thermal map around 244 s and 428 s after the end of the heating phase respectively for the heating time of 120 s and 240 s, allow identifying the defects shown in Fig. 14. In practice, the minimum dimension of the detectable defect is 10 mm and the presence of defects having a diameter of 5 mm does not produce any measurable variation of the thermal map, as observed before discussing the results of the numerical model. These results are a direct consequence of the inherent difference existing between SMART and pulsed

Fig. 10 Comparison of experimental and numerical evaluation of absolute contrast: **a** traditional thermography with heating time of 3 s; **b** SMART thermography with heating time of 240 s

thermography. The first difference is relevant from a quantitative point of view: the amount of heat flux that characterizes the two techniques is deeply different. In pulsed

thermography the heat power given by halogen lamps is able to produce a sufficient increase of temperature using a heating time t_h of 3–10 s, while SMART thermography requires long heating time t_h (from 120 to 240 s). Nevertheless the high uniformity of the temperature obtained in SMART thermography allows reducing the increase of temperature to carry out a reasonable inspection, the limitation in the heating does not allowed the detection of defects with dimension lower than 10 mm. The cause is originated by the fact that the thermal input is insufficient to produce a measurable variation of the thermal flux. As preliminary tests carried out at lower heat power showed a further reduction of the detection capability and an unacceptable worsening of experimental data, which became of the same magnitude of instrumental resolution, authors retained that it would be possible to reduce the minimum dimension of visible defects applying a higher heat power density. In order to verify this statement, authors carried out further numerical simulations increasing the applied electric power from the initial value of 11.7 W up to 13 (+ 11.1%) and 15 W (+ 28.2%). Data of absolute contrast for these numerical simulations are reported in Table 6, which clearly show not only the increasing contrast of the already visible defects but also the possibility to detect minor defects with acceptable contrast. However, this numerical confirmation gives a useful indication, but requires an experimental verification to be already accepted, since also spatial resolution of thermal images becomes relevant for an effective detection capability.

The second difference is relevant from a qualitative point of view: the defects appear as lower temperature regions, due to the reduction of the thermal conductivity introduced by the defect, that act as a thermal shield. A similar situation is observed when thermal inspection is

Fig. 11 Thermal processing defect with traditional thermography and different heating time: **a** 3 s; **b** 10 s

Fig. 12 Absolute contrast **(a)** and normalized contrast **(b)** for the traditional thermography (heating time 3 s)

Fig. 13 Absolute contrast **(a)** and normalized contrast **(b)** for the traditional thermography (heating time 10 s)

Table 5 Absolute and normalized contrast for the traditional thermography

Defect	Diameter d (mm)	Depth h (mm)	Heating time 3 s		Heating time 10 s	
			Absolute contrast Ca_MAX (°C)	Normalized contrast Cn_MAX (°C)	Absolute contrast Ca_MAX (°C)	Normalized contrast Cn_MAX (°C)
d1	25	3	0.630	0.0242	1.996	0.0314
d2	25	4.5	0.235	0.0175	0.745	0.0297
d3	15	3	0.575	0.0149	1.814	0.0217
d4	15	4.5	0.229	0.0063	0.705	0.0126
d5	10	3	0.433	0.0159	1.333	0.0213
d6	10	4.5	0.113	0.0066	0.406	0.0136
d7	5	3	0.191	0.0056	0.545	0.0074
d8	5	4.5	0.046	0.0046	0.079	0.0042

carried out in transmission, positioning the heat source and IR camera symmetrically with respect to the inspected component. Effectively SMART thermography must be regarded as a specific transmission technique, since the

heat source is opposite to the IR camera position. This fact is clearly showed by the characteristic negative values of the absolute contrast C_a (Figs. 15a, 16a). An important consequence is that it is possible to detect only the defects

Fig. 14 Thermal processing defect map with SMart thermography and different heating time: **a** 120 s; **b** 240 s

Table 6 Numerical absolute contrast for the SMart thermography applying increased power

Defect	Diameter (mm)	Depth (mm)	Absolute contrast Ca_MAX (°C)		
			P11.7 W	P13 W	P15 W
d1	25	3	-0.164	-0.231	-0.268
d2	25	4.5	-0.176	-0.270	-0.264
d3	15	3	-0.173	-0.224	-0.260
d4	15	4.5	-0.151	-0.263	-0.306
d5	10	3	-0.229	-0.237	-0.276
d6	10	4.5	-0.178	-0.261	-0.304
d7	5	3	-	-0.235	-0.273
d8	5	4.5	-	-0.236	-0.275

that are comprised between heat source and IR camera, suggesting the need to introduce the wire grid at the highest depth.

The curves reported in Figs. 15, 16 are affected by a not negligible noise, since the measured values are close to the sensitivity of the IR camera detector. However, nevertheless the thermal difference between the defect area and the nearest intact area is relatively low, about 0.15–0.20 °C, the individuation of defects and the calculations of the contrasts is easily accomplished. Maximum values of the absolute contrast are obtained immediately after the end of the heating phase, suggesting the possibility to avoid using long observation time after the end of heating time. This observation is relevant since the amount of data collected for SMart thermography is higher than traditional thermography. This is obvious, since the applied heat power is limited in SMart thermography, thus determining a slow heating and cooling phase. This fact could be a potential problem in case of inspection of large components, but the possibility to use a window recording across the end of heating time that will capture the more interesting thermal phenomena allow overcoming this difficulty.

Fig. 15 Absolute contrasts **(a)** and normalized contrast **(b)** for SMart thermography (heating time 120 s)

Fig. 16 Absolute contrasts **(a)** and normalized contrasts **(b)** for SMART thermography (heating time 240 s)

Behaviour of normalized contrasts curves differ from the typical ones of traditional thermography, since after an initial growth normalized contrast tends to be stable for the whole observation time (Figs. 15b, 16b). All the data of defect are synthetically resumed by the maximum values of absolute C_a and normalized contrast C_n reported in Table 7.

Another important consideration concerns the possibility to obtain at least a qualitatively indication about the depth of defects. Despite the thermal contrast values strongly depend on the choice of the intact and defective zone, the maximum value of C_a in the traditional thermography resulted higher for superficial defects respect to the deeper defects both in the experimental and numerical data (Fig. 17). Moreover, for superficial defects, the absolute contrast C_a increases with defect size. On the contrary, the absolute contrast in the case of SMART thermography appeared to be independent on depth and defect size both in experimental and numerical case (Fig. 18). It is however possible to observe a certain similitude between experimental and numerical

trends in both cases, which confirms again the reliability of the numerical model.

5 Conclusion

The possible advantages of the adoption of a multifunctional composite material for the realization of wind blades have been discussed. This multifunctional material, obtained adding SMA wires to a unidirectional glass fibre and epoxy matrix, could meet the requirements of protection against lightning damages and, at the same time, could overcome the difficulties of carrying out active thermography inspections on large components as wind blades. The improvements in the field of the protection against environmental phenomena like lightning, associated to a better detectability of in-service defect could determine a remarkable extension of the wind blade life and reduction of maintenance procedure.

Limiting the study to the problem of detecting efficaciously the in-service defects of wind blades, the proposed

Table 7 Absolute and normalized contrast for the SMART thermography

Defect	Diameter d (mm)	Depth h (mm)	Heating time 120 s		Heating time 240 s	
			Absolute contrast C_{a_MAX} (°C)	Normalized contrast C_{n_MAX} (°C)	Absolute contrast C_{a_MAX} (°C)	Normalized contrast C_{n_MAX} (°C)
d1	25	3	-0.1418	0.0047	-0.1570	0.004658
d2	25	4.5	-0.1672	0.0060	-0.1562	0.00634
d3	15	3	-0.1454	0.0059	-0.1429	0.00460
d4	15	4.5	-0.1143	0.0050	-0.1831	0.00632
d5	10	3	-0.2559	0.0103	-0.1658	0.00570
d6	10	4.5	-0.0706	0.0034	-0.1491	0.00540
d7	5	3	-	-	-	-
d8	5	4.5	-	-	-	-

Fig. 17 Absolute contrasts vs defect size for experimental (a) and numerical (b) traditional thermography

Fig. 18 Absolute contrasts vs defect size for experimental (a) and numerical (b) SMART thermography

thermographic technique, called SMART thermography, has been compared to traditional pulsed thermography for the detection of artificial defects in a representative panel. In particular the study has been carried out on a panel with limited dimension suitable to be inspected in laboratory, in order to limit the complexity of the approach and to explore the possibility of the technique. The experimental results showed that SMART thermography allow obtaining a high uniformity of the superficial temperature at the end of the heating phase without a particular care on the set-up procedures. Moreover, defects having a minimum diameter of 10 mm are clearly individuated with good accuracy. Defects with a characteristic dimension of 5 mm were not detected with SMART thermography, thus differing from the traditional technique. However, it has been showed through numerical simulations that increasing the heat power also the smallest defects would be visible with this technique. Another peculiarity of SMART thermography is the low heat power that is possible to apply

during inspection: this circumstance has the advantage to determine a low increase of material temperature and the disadvantage to require long heating time and observation time for the inspection. However, the relatively high amount of data could be reduced considering that thermal data elaboration for a short time after the end of heating phase is sufficient for an adequate characterization of defects.

The experimental work has been supported by a numerical transient FEM model, conceived as a useful tool for planning the inspection of a component. The thermal parameters of the materials have been assumed on the basis of literature data and tuned on the basis of the simulation of the traditional thermographic technique. The same parameters have been successfully used to simulate the SMART thermography, without the need of an additional tuning of the parameters. The validity of this last FEM model is showed by the fact that the model predicted the impossibility to detect the defects of 5 mm diameter.

Finally, the absolute contrast has been related to the depth of the defect both experimentally and numerically. Traditional thermography seems to capture some indications about the depth of the defect, whilst SMARt thermography is not able to give information about this, probably due to an insufficient external heat source.

Despite of all, SMARt thermography showed to have the potentiality to reach the same degree of reliability of the traditional pulsed thermography, having the evident advantage to do not require an external heat source and reducing time set-up. However, the limitation of the applied heat source could limit the detectability of defects under a certain dimension.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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