Guidelines for Aircraft Composite Panels

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Abstract: *The objective of this paper is to give a general perspective and present some elementary steps for manufacturing aircraft sandwich panel composites. Composite materials have been widely used in high performance sectors of the aerospace and automotive industry, and there is considerable knowledge and confidence in their static, dynamic and crashworthiness properties. Sandwich composites are becoming more and more used in airframe structural design, mainly for their ability to substantially reduce weight while maintaining their high mechanical properties. The steps for manufacturing a sandwich composite that meets all the requirements for exploitation are very precise and rigorous, involving specific design requirements, specific materials selection and specific manufacturing conditions starting with the lay-up procedure and up to the curing process inside an autoclave. After the curing process, destructive and nondestructive tests and experiments are performed on the composite structures in order to validate the products. At the same time, this paper presents a short briefing about the implication of 3D printing technologies with high temperature resistance resins for sandwich cores used in aerospace applications.*

Key Words: *aviation industry, composite materials, 3D printing, lay-up manufacturing, sandwich panels, honeycomb core*

1. INTRODUCTION

This paper aims to provide essential information about composite materials manufacturing with a short reflection on how advanced materials are used for obtaining the skins and cores for composite sandwich panels. An overview on how the new 3D printing technologies bring time-cost optimization techniques and a technological solution for an aircraft sandwich composite panel using 3D printed elements is presented. General considerations about composites design focusing on ply orientation, thicknesses and symmetry aspects are briefly discussed. Sandwich structures have found application in aerospace engineering due to their high strength to weight ratio. This type of construction consists of thin, stiff and strong sheets of metallic or fiber composite material separated by a thick layer of low density material, commonly known as core material (light foam type or honeycomb). For this reason, a comparison between foam cores and honeycomb cores is presented below to emphasize the advantages and disadvantages of each type of structure. Moreover, a composite manufacturing and a curing process inside an autoclave for an aircraft honeycomb sandwich panel with skins made from carbon fabrics reinforced polymer (CFRP) is described from the beginning with the lay-up process to the advanced stage when nondestructive testing (NDT) is performed.

2. COMPOSITE MATERIALS CONSIDERATIONS

2.1 General design considerations

The difference between composites and metals is that composite materials are uniaxial in their single ply state, with very high mechanical properties along their longitudinal axis and low properties along their transverse axis.

The directional nature of composite laminate allows the ability to construct a material which can meet stiffness requirements and specific loads without wasting material. If this material is adhered to restraining members, all of the fibers may be so oriented, if the design requirement is simply to provide stiffness or axial strength, a high percentage of the material should be unidirectionally oriented [3].

By definition, a laminate is made up of two or more plies with the same or different orientations working as a whole element. To simplify design and stress calculations, the most common directions used are 0°, + 45°, 135° (- 45°) and 90°, 0° being the main stress direction or loading axis. The correct ply orientation gives a structural element the ability to support loads acting in different directions.

Some generic rules that should be followed in the process of designing composite parts are those regarding stacking sequence [4].

- Balanced

The laminate should be balanced, that means for each ply in positive direction there is a ply in negative direction. If perfect balance is not possible, the "unbalance" shall be kept as close as possible to the middle plane.

- Symmetry

The stacking sequence should be symmetric around the neutral axis: for each ply in positive direction at a distance X of the middle plane there is a ply in positive direction at a distance -X. If perfect symmetry is not possible, the asymmetry must be kept as close to the middle plane as possible.

- Regular distribution of layer orientation

Those layers who have the same orientation should be uniformly distributed throughout the stacking sequence to minimize coupling effects and ensure a homogeneous stress distribution throughout the laminate.

- Maximum grouping

The maximum number of plies grouped together in the same direction is limited, this maximum number depends on the ply thickness. It is recommended to use a maximum number of three plies [4].

For this paper, an aircraft honeycomb sandwich panel is considered to be discussed.

2.2 Skin considerations for sandwich composites

A sandwich composite structure consists of skins or laminates with a much thicker (in relation to the skins) structural core in between that is attached with adhesive layers. It is the sandwich structure as a whole that gives the positive effects, however the core has to fulfill the most complex demands. When the local pressure is high, the faces should be dimensioned for the shear forces connected to it. To keep the faces and the core working together the adhesive or bonding layer between the faces and the core must be able to transfer the shear forces between them.

The adhesive must be able to withstand shear and tensile stresses. A simple rule is that the adhesive should be able to take up the same shear stress as the core. It is of utmost importance that the skins properly adhere to the core to give the expected structural behavior. Carbon–

epoxy prepregs are generally used to form the skins of honeycomb sandwich structures. One of the most advanced techniques for making composite components is by using prepreg carbon fiber reinforcement, cured under heat and pressure to produce professional quality parts with a high quality surface finish, low resin content and excellent structural performance [15], [16].

Skins are resulting from the combination of reinforcing fibers with a polymer matrix leading to a high performance material allowing weight reduction of more than 20% compared to aluminum. To achieve high mechanical performance it is also important to have a high volume fraction of fibers in the material (typically 55-60%), to avoid fiber curvature of misalignment and to limit the void content in the resin (typically <3%) [16]. A thin adhesive film is used as interface between core and the first ply of the sandwich skins.

The outer skins of the composite parts are electrostatically charged during exploitation and this fact is considered a risk for lightning strikes. In order to minimize this risk, companies like Boeing and Airbus developed protection systems that use a metal mesh [7], as shown in Figure 1, made of aluminum or copper attached to the outer surface of the composite parts, in order to increase the electrical conductivity of the aircraft's structure.

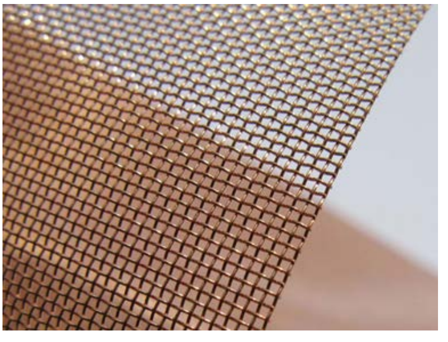

Fig. 1 Copper wire mesh [9]

2.3 Short overview on core materials

Composite cores are usually made from very lightweight materials such as foams or honeycombs. The core's function is to support the thin skins so they do not buckle (deform) inwardly or outwardly, and to keep them in relative position to each other. To accomplish this, the core must have several important characteristics. It has to be stiff enough to maintain a constant distance between faces. Also, it must be so rigid in shear that the faces do not slide over each other.

Foam cores are the most commonly used in sandwich structures. They can be manufactured from a variety of synthetic polymers such as polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), polymethyl meth acrylamide (acrylic), polyetherimide (PEI) and styrene acrylonitrile (SAN). They can be supplied in densities ranging from less than 30 kg/m^3 to 300 kg/m^3, although the most used densities for composites structures range from 40 to 200 kg/m^3. Their thicknesses are usually from 5mm to 50mm. Polymethyl meth acrylamide foams such as Rohacell® offer some of the highest overall strengths and degree of stiffness for composite cores. These materials have high dimensional stability which makes them unique in that they can readily be used with conventional temperature curing prepregs. The main disadvantage of these materials is the expensive cost which make their use limited to aerospace composite applications such as structural panels and command surfaces [3]. For open cell periodic cellular structures, foam can be used to fill the cavities of the core to enhance the energy absorbing function [6].

Honeycomb cores use the geometry to allow the minimization of the amount of used material to reach the minimal weight. This geometry can vary widely but the common feature of all such structures is an array of hollow cells formed between thin vertical walls. These cells are often columnar and hexagonal in shape. The honeycomb shaped structure provides a material with minimal density and relative high out-of-plane mechanical properties. Honeycomb cores are available in a variety of materials for sandwich structures, from low strength and stiffness for low loads applications to high strength and stiffness, extremely lightweight components for aircraft structures. There are two major types of honeycomb cores: metallic and nonmetallic [3].

Designers must be aware that aluminum does not come in direct contact with carbon skins since the conductivity can increase the risk of galvanic corrosion. Nomex honeycomb is the most common nonmetallic structure for sandwich composites. This is made from Nomex paper – a paper based on Kevlar™ instead of cellulose fibers. The initial paper honeycomb is soaked in a phenolic resin to produce a honeycomb with high strength and very good fire resistance. Nomex is widely used for lightweight interior panels for aircraft in conjunction with phenolic resins in the skins. Like aluminum, honeycomb has a high strength to weight ratio and corrosion and fungus resistance but has the added benefits of flame retardancy, good thermal insulation and is suitable for 3-D shapes. For the core material, Nomex aramid honeycomb with 15mm thickness was considered. This material is shown in Figure 2.

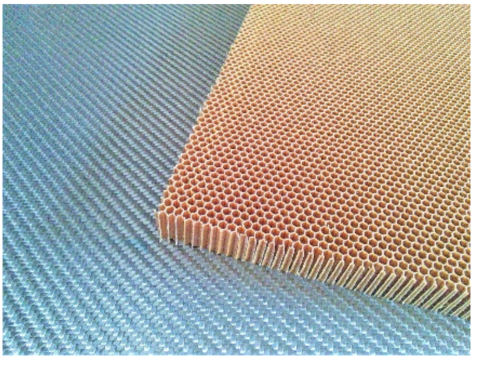

Fig. 2 Nomex aramid honeycomb [18]

The core material is normally low strength material, but its higher thickness provides the sandwich composite with high bending stiffness with overall low density [11]. For example, a comparison between a sandwich panel with a 17 mm thickness and a steel panel with 5 mm thickness subjected to the same bending effort is illustrated below in Figure 3. It can be seen that for the same criteria for deflection, the net weight savings with sandwich design is up to 90%.

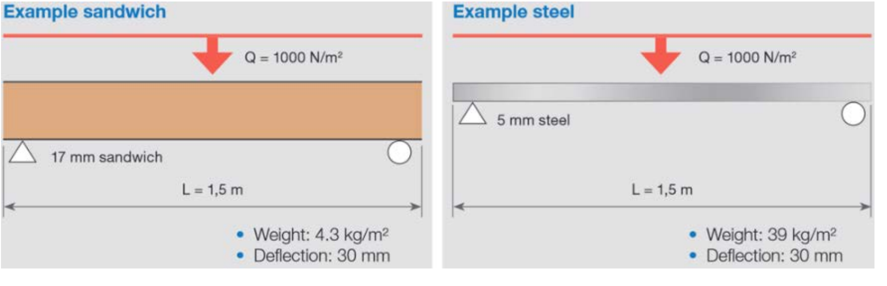

Fig. 3 Comparison between the performances of a sandwich panel and a steel panel for the same deflection criteria [2]

As consequence, studies showed that stiffness to weight ratio increases exponentially by increasing the thickness of the core. This feature is presented in Figure 4.

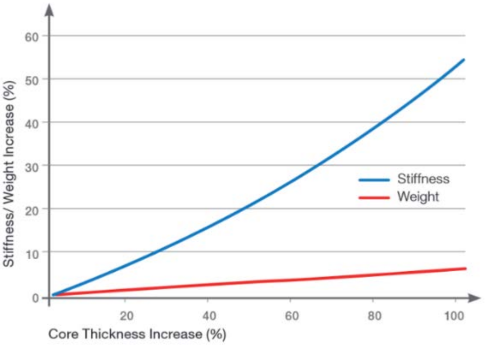

Fig. 4 Effect of how increased core thickness yields increased stiffness to a relatively low weight penalty [2]

The reasons for aircraft engineer's choice of a honeycomb panel rather than more conventional materials include [8]:

- High strength-to-weight ratio,
- Superior surface smoothness,
- Thermal insulation,
- Acoustic dampening,
- Buoyancy,
- Corrosion resistance,
- Excellent resistance to mechanic and sonic fatigue,
- "tailored to fit" feature.

Some of the disadvantages core materials are presented below:

- A good quality control is required during the manufacturing process to ensure that there is no disbonding in the adhesive layer.
- Corrosion problems appear due to in-service trapped moisture the core material.
- The load carrying capacity of structures is reduced if the disbonds may initiate and propagate in the adhesive layer during service.

For this paper, a 15mm thick nonmetallic Nomex honeycomb core with 48 kg/m^3 density and 3.2mm cell size shall be considered for the construction of the composite sandwich panel. The outer skin is made from three layers of carbon-epoxy prepregs with 45/0/-45 orientation, one layer of copper mesh for electrostatic discharge and one layer of glass fiber for protection. The inner skin is made from two layers of carbon-epoxy prepregs with 45/-45 orientation and one layer of polyvinyl fluoride film that protects the honeycomb from moisture. The entire lay-up can be observed in Figure 5.

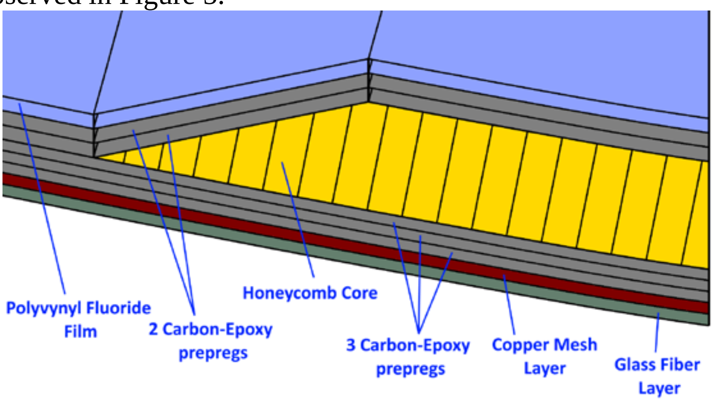

Fig. 5 Lay-up for an aircraft composite sandwich panel

2.4 3D printing technologies for aerospace sandwich panels

Nowadays, 3D printing technologies and aerospace engineering started to cover a more and more expandable common ground. There are a lot of materials that can be 3D printed to produce aerospace components. One of these materials is Polyetherimide (PEI), an amorphous, amber-to-transparent thermoplastic with glass transition temperature up to 217 °C, able to resist high temperatures, inherent flame resistance, high dielectric strength and extremely low smoke generation.

An approach to the manufacturability of composite cores made with 3D printing technologies is that the core can be printed and also used as tool for the lay-up process for a sandwich panel. This core is made from ULTEM resins [12], [13], [14] and can withstand autoclave high temperatures and pressure cycles. The core material and geometry can be customized in order to respond to specific loads or to adapt specific technological conditions such as surface roughness or insulation [10].

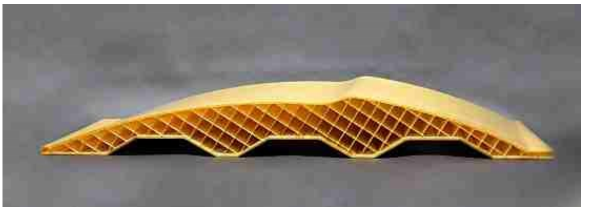

Fig. 6 ULTEM 1010 tool for Dassault that can stand up to autoclave pressures and cure temperatures [10]

There are many advantages for using 3D printing technologies for sandwich panel manufacturing. Some of the best advantages are:

- No lay-up tool required,
- Reduction of the overall manufacturing time and costs,
- Increased mechanical properties of the composite (the core can be a 3D printed closed structure with covered faces increasing the adhesion of the skins),
- Very good dimensional stability,
- Possibility to adapt the structure's stiffness to load directions,
- High potential for component manufacturing with zero chances of material losses in comparison with classical manufacturing technologies.

This paper offers some innovative technical solutions for 3D printing applications for stiffening core edges and replacing the usage of inserts with longitudinal 3D printed elements. A transversal section through the panel that contains 3D printed elements can be observed in Figure 7.

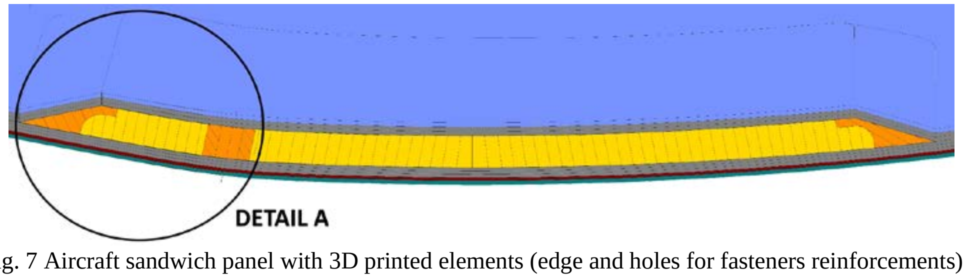

Fig. 7 Aircraft sandwich panel with 3D printed elements (edge and holes for fasteners reinforcements) – transversal section

In Detail A the same lay-up configuration as described before can be seen. The only difference is the fact that the honeycomb core is milled to fit between edge reinforcements. These reinforcements, which are designed all around the honeycomb core, allow a better alignment of the core on the 3D shaped composite panel and provide a better strength to external loads. Moreover, with 3D printing technology, reinforced holes for fasteners can be created. This elements are representing in Detail A from Figure 8.

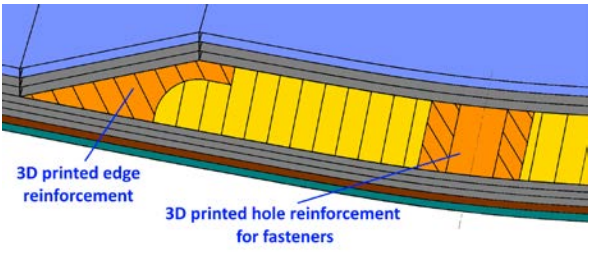

Fig. 8 Detail A presenting the 3D printed reinforcements elements

The reinforced holes for fasteners installation can be connected to each other and with the surrounding 3D printed edge structure in order to increase the material strength. This aspect is represented in Figure 9.

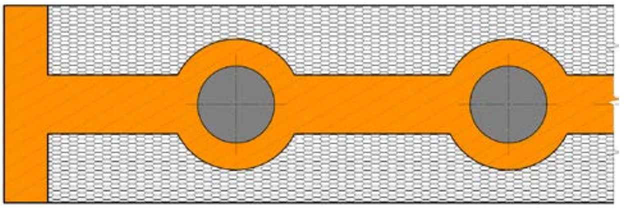

Fig. 9 Top view inside the composite panel showing 3D printed elements connected with each other surrounding the honeycomb core

Based on recent tests, this 3D printing technology can be applied on large scale in the near future for the manufacturing of aircraft structural components.

3. TECHNOLOGICAL FEATURES

3.1 Manufacturing process

Once the final design of the sandwich panel is ready and the materials are procured, the manufacturing process can begin. The operations for manufacturing an aircraft composite sandwich panel are listed in Figure 10.

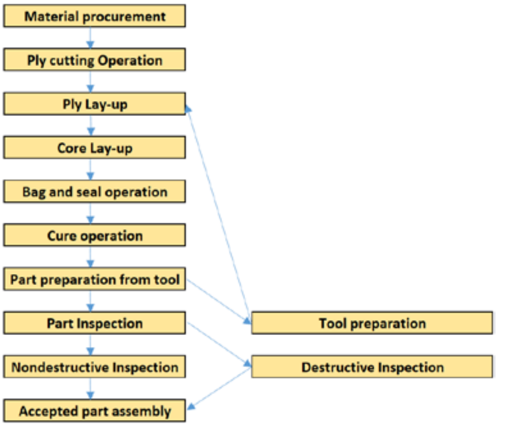

Fig. 10 Diagram of composite manufacturing process [1]

Soft tooling is the name for the molds made out of composite materials. The main problem in terms of composite tooling is the capability to withstand many production cycles.

Hard tooling, also named metal tools, have several advantageous features such as fast turnaround time to create highly complex-shaped mold tooling for high volume production. However, in order to guarantee a flawless lay-up, the hard tooling must have no defects, considering the fact that even a minor defect could destroy the integrity of the part. Metal alloy tooling materials like *Invar* offer a closer coefficient of thermal expansion match very near to that of carbon fiber composites [19].

The composite parts are formed in lay-up tools or molds which can be made from any material that meets all the technological requirements. There are many issues involved in election of mold tools because any desirable properties come at a price. The high-performance composite are generally formed in carbon fiber, castable or monolithic graphite, ceramic and metals (alloys).

For this paper, a composite manufactured lay-up tool was considered. The composite used for the mold consists in carbon fabric layers reinforced with Epoxy resin. The mold is placed on a steel platform to allow the transportation to the autoclave. These elements are shown in Figure 11.

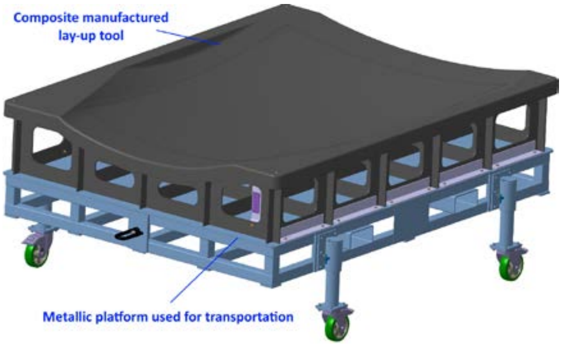

Fig. 11 Lay-up tool used for the manufacturing

They lay-up process begins once the mold preparation is complete. After the surface is polished, a release agent that can withstand autoclave temperatures must be applied. Most mold release waxes will not perform well at autoclave temperatures and it is recommended to never use release wax with prepregs.

On a typical aircraft composite panel the lay-up can be done by hand or using an automated machine depending on a multitude of factors such as level of production, complexity of geometry, cost etc.

For simplicity, the lay-up order is presented from bottom to top. First component to be created is the outer skin. The glass fiber used for protection represents the first layer used for bedding on the lay-up tool and then copper mesh layer is added to the sequence for electrostatic discharge during exploitation. The three layers of carbon-epoxy prepregs are positioned over the copper mesh.

Each ply has thin adhesive face sheets that helps agglutination of neighboring plies. With these five layers the outer skin is complete. A thin adhesive film [17] is added to seal the 15 mm thick Nomex honeycomb from the outer and inner skins. After the honeycomb is added, the process to lay-up the inner skin can begin. Over the adhesive film, two carbon-epoxy prepregs are laid up and on top of them a polyvinyl fluoride film that protects the honeycomb from moisture is attached. The lay-up for the aircraft composite panel is now complete and the result can be seen in Figure 12.

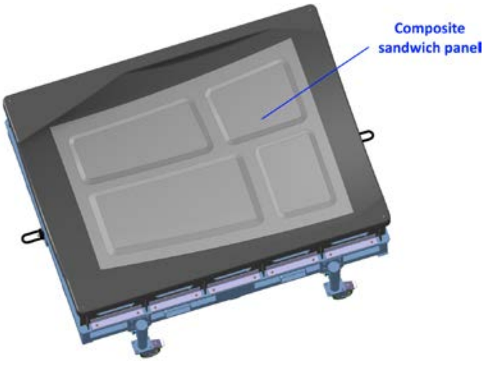

Fig. 12 Aircraft composite panel placed on lay-up tool

Once the lay-up process is completed, the preparations for the vacuum process begin. In this phase, a strip of vacuum bag sealant tape is paced around the periphery of the mold. Choosing the right size of the vacuum bag is essential. If the vacuum bag is too small may cause the bag to stretch (also known as "bridging") which could cause a rupture during the cure. Allowing for approximately 30% to 40% excess of vacuum bag is a good starting point for complex shapes [20]. After the vacuum bag is placed, a "thru the bag" vacuum connection and a vacuum gauge for detecting any leaks are installed. A vacuum integrity check should be undertaken on the final bag before placing in the autoclave for curing. After the vacuum process is complete, the autoclave treatment can begin. The curing operation is made inside an autoclave which uses a pressure chamber to apply heat and pressure during the consolidation process. Autoclave method is the most common and economical method used in the aerospace industry to make composite parts. These machines are generally programmable and temperature/pressure parameters can be automated. The vacuum begins at -1bar and drops to -0.1bar when the autoclave pressure raises. The maximum pressure inside the autoclave is between 5-7 bars. The heating rate is typically 0.3 to 0.5°C/min. The cure cycle duration starts when a thermocouple embedded near the prepreg reaches the nominated cure temperature. The cooling rate is typically 0.5°C/min under vacuum and pressure. The maximum temperature for the cycles reaches at least 180°C. Heat-up rates are dependent on component thickness, for example, slow heat-up rates should be used for thicker components and large tools. Accurate temperature measurements of the component should be made during the cure cycles by using thermocouples [5]. For this sandwich panel, the autoclave temperature and pressure parameters are shown in Figure 13. After the autoclave cycle is complete, the composite is taken out of the autoclave and is being prepared for testing and assembling.

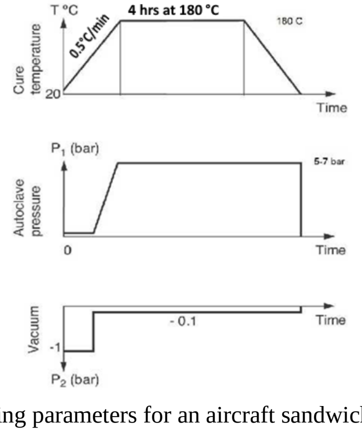

Fig. 13 Curing parameters for an aircraft sandwich panel [22]

3.2 Non-destructive testing methods of composite materials

Non-destructive testing (NDT) refers to the evaluation and inspection process of materials or components for characterization or finding defects and flaws in comparison with some standards without altering the original attributes or harming the object being tested. NDT methods include contact and non-contact methods and have their specific applications in testing and evaluating the composites. Different non-destructive control methods are used during production and maintenance to ensure the safety of the components.

Active thermography is an effective method for rapid inspection of large surfaces, in a non-contact way. Due to the stratified structure of the composite materials, different types of defects can occur – which are completely different from those of metals: delaminations/ separations between layers, inclusions of air (porosity) and blows, etc. The blows are particularly critical, as they are difficult to recognize from the outside, even if severe damage occur inside. Optical excitation thermography methods can reliably detect those defects, and therefore play an increasingly important role in examining safety-relevant components.

The installation used for active thermography is presented in Figure 14.

Fig. 14 Installation used for active thermography [21]

Benefits	Detectable defects
• Imaging method	• Delamination
• Measurements made in depth	• Hits
• Testing of complex geometries	• Porosity
• High reproducibility	• Bonding of metal inserts
• Large- scale inspection (square meter)	• Volume of fibers
• No contact	• Characterization of semi-finished products
• Easy to use	• Characterization of adhesive joints
	• Wall thickness measurements
	• Inspection of repaired points
	• Detection of water inclusions.

Visual Testing should be the most basic type of NDT that many instances use because it can save both time and money. The most important advantage of the visual inspection is its quick process. The other advantage of visual inspection is the relative affordability of the process. The visual inspection needs no equipment but this method has its disadvantages.

Radiographic Testing (RT) is the most commonly used testing method. The most common type of damage to composites is a delamination resulting in an air pocket; a delamination can only be seen in RT if its orientation is not perpendicular to the X-ray beam. There are many types of radiography and each has specific applications. Conventional radiography is the most useful when the parts are neither too thick nor too thin. These types of radiography are useful in detecting large voids, inclusions, translaminar cracks and non-uniform fiber distribution [24].

Defects can inadvertently be produced in composite materials. It is clear that in many ways, a composite can differ from the ideal either during manufacture or in service. The extent to which any of these deviations from ideal should be considered as a defect is a function of the intended use of the material and the significance of the deviation on the required performance. All defect types are known to adversely affect performance in some way. However, the type and size of defect that needs to be found can only be set for each application based on the results of mechanical destructive tests and a detailed knowledge of how such defects grow, if at all, in the expected service environment. This process sets the acceptance criteria for manufacturing and in-service defects.

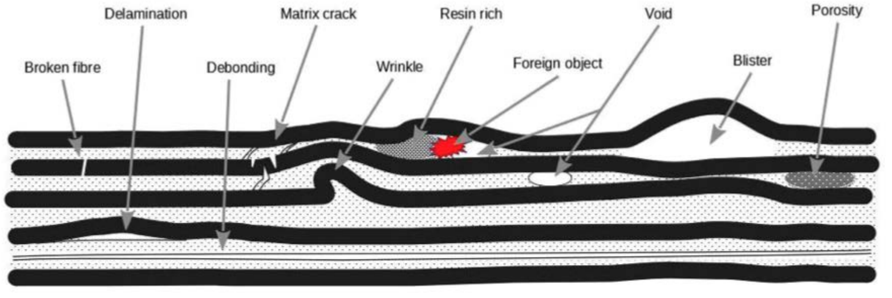

Fig. 15 Common defects in composite materials [23]

The composition and properties of engineering alloys are controlled by industry standards or materials specification from organizations such as ASTM, CDA, AA and SAE.

It is beyond the scope of this article to discuss the significance of defects in detail but it should be stressed that defect significance must be assessed before meaningful acceptance and rejection criteria can be established. Most common defects are shown in Figure 15.

4. CONCLUSIONS

This paper presented some guidelines for design and manufacturing stages of an aircraft honeycomb composite sandwich panel. Some general design considerations about lay-up sequence and constitutive elements of a sandwich composite were briefly discussed. General aspects of composites and how they are manufactured are well known and this paper aimed at bringing into discussion an innovative element such as the implication of 3D printing technologies with high temperature resistance resins for sandwich cores that brings a large multitude of advantages over the classic lay-up procedures. It is possible that production tooling to be made in a short time and on-demand, fact that helps the tooling industry to keep pace with accelerating composite design cycles towards an overall time-cost optimization. Moreover, a composite sandwich panel with specific elements was proposed for the discussion of the manufacturing process. This process involved a composite manufactured lay-up tool that can withstand autoclave temperature and pressure cycles. The lay-up procedure and autoclave curing process were described for a specific honeycomb sandwich panel. Non Destructive Testing methods for aircraft composite materials were briefly introduced in order to create a perspective about the defects that can occur inside the structures.

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