A Novel Live Failure Detection Method for Composite Material Systems

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***Abstract*— This paper presents an analysis of composite structures and fault detection mechanisms with reference to aerospace and sport applications. This work introduces a novel live failure detection and critical failure prevention mechanism primarily for composite materials. Firstly a bicycle system is studied and used as the basis for the investigation. Further research and development is carried out on a quadcopter system to investigate the practical applicability of the live structural failure detection method. The results indicate that the live failure detection method is one of the best possible methods to prevent critical failures in such systems when to compared to available systems today.**

***Index Terms*—fault detection, control structure, quadcopter system, live failure detection, bicycle, condition monitoring**

I. Introduction

Composite materials are constructed from two or more materials of differing properties that are combined to produce a new material [1]. It is important to recognize that each of the constituent materials remains distinct chemically and physically in the new material. The constituent materials function synergistically to create a composite material that has enhanced properties when compared with the individual constituent materials. The interest in advances in materials and the development of health monitoring solutions has nowadays gained considerable attention from several researchers (see, for e.g. [2, 3].) However, it is important to note that despite the advances in materials there are little health monitoring solutions available when in use [2]. Super materials such as carbon fibres are becoming increasingly popular due to their inclusion in composite materials, the gradual reduction in production costs over recent years has allowed its widespread use. Formerly such materials were only viable in high end sectors such as aviation due to such high costs, but have now trickled down to products that are affordable to even the modest hobbyist (e.g. bicycle).

Failure detection methods of composite material systems are currently the subject of much research effort in the composite material community at large; see for example [2–4] using a variety of failure detection methods and control algorithms. For enhanced reliability, early failure detection methods with critical failure prevention are preferable. Therefore, early failure detection techniques have become increasingly popular in the composite material systems community. Live failure detection techniques in composite material systems offer a structured approach to resolve failure related issues giving essential early indication and warning. Such an approach gives an alternative direction when compared to offline non-destructive failure detection methods. In this paper, details of a live failure detection technique are discussed, in addition a brief overview of the characteristics of composites materials and the common defects are also presented. Finally, applications and conclusion are presented.

II. Composite Materials Structures

Composites are formed by using the principle of combined action. The basic idea is that for the new material a better combination of properties can be achieved by combining two or more distinct materials [1].

The individual materials used to make up the composite are the constituent materials. There are two main categories of constituent materials: the matrix and reinforcement. At least one portion of each type is required for a composite. In such, the reinforcement are the fibres that are used to fortify the matrix in terms of strength and stiffness. The reinforcement fibers can be adjusted in different ways to affect the properties of the resulting composite. The matrix, typically a form of resin, keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack, and it bonds the reinforcement so that applied loads can be effectively transferred [5]. Most of the composites that are available on the market are produced by using a polymer matrix material, so-called resins. Depending on the initial raw ingredients, the polymer type will differ and so there are many different types of polymers available. However, the most common is epoxy.

Epoxy adhesives are regarded as the strongest of all adhesives and so is commonly utilised in the most demanding applications such as vehicles, planes, boats and sporting equipment. It is a petroleum based adhesive that is free of solvents, has superior bonding properties, extreme durability and high resistance to chemicals and heat. Epoxy's contain the important element epichlorohydrin which forms a hard layer that is highly resistant to both high and low temperatures as well as moisture. To highlight the excellent benefits of epoxy

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resin a comparison between polyester resin are as follows: **Bond strength**: Epoxy's relative strength can hold as much as 2000 lbs per square inch whereas polyester is less than 500 lbs per square inch.

Resistance: Epoxy is far more resistant to wear, cracking, peeling, corrosion, chemicals and the environment. It is also highly moisture resistant, which allows particular formulas of epoxy to actually be applied whilst fully submerged in water. Polyester resin has minimal resistance to moisture and is considered water permeable and is therefore open to fractures. Due to polyester being more fragile it is preferred on low stress applications or temporary fixes.

Cure time: Both epoxy and polyester resin cure time vary and this is due to the formulation of the resin and the cure temperature at use. Resins generally have a quicker cure time which is frequently seen as a benefit however this is dependent on the task at hand. The temperature can be manipulated to achieve a cure time more closely matched to what is required provided the temperature is within that specified from the supplier's technical data sheet.

Odour: Polyester is notorious for being unpleasant to work with even after curing, although it sets much faster. Epoxy resin has much less odour, nevertheless suitable breathing apparatus should be worn when working with any type of resin.

Shelf life: Epoxy products have a far greater shelf life of several years with no loss of potency provided the resin and hardener are not contaminated or mixed. Polyester is much more fragile over time, again specifics on each type can be found on the manufacturers technical data sheet as to exact characteristics and properties.

Cost: Due to the strength and formulation requirements epoxy resins suffer in terms of cost when compared with other adhesives and gives a justifiable reason to when it is not used. On low cost items such as inexpensive jewellery it can be difficult to justify the high cost of epoxy resin and so lower spec adhesives are deemed more suitable. A typical epoxy structure is shown in Fig.1.

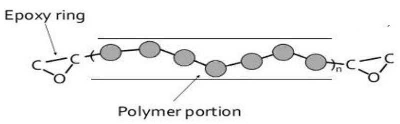

Figure 1. Epoxy structure

Epoxy resin (Fig. 2) also called "epoxy" or "polyepoxide". Second most widely used family of thermosets copolymer (after polyesters) [6].

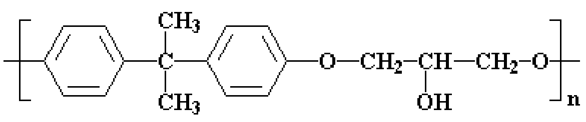

Figure 2. Epoxy resins

The aromatic structure of the resin implements a strong hydrophobic performance far over competitive resins like polyurethanes or acrylics, which were developed at the same time [5]. Therefore, the advantages of epoxy systems are that it has an excellent adhesion and low shrinkage on cure typically > 3%. Furthermore it has, excellent water, heat and chemical resistance, versatile and no release of volatiles during curing.

Carbon fibres are classified by the tensile modulus known as Young's modulus which quantifies the stiffness of an elastic material. Young's modulus predicts how much a material bends or extends under tension or shortens under compression, the higher the Young's modulus the stiffer the material. It is worth noting that the Young's modulus is not consistent across all orientations of a material and this is true of carbon fibre. When a materials mechanical property are the same in all directions it is known as isotropic, Carbon fibre is anisotropic as it has a higher Young's modulus, when the force is parallel to the fibres. Carbon fibres can be grouped into; Ultra high modulus of type UHM (modulus > 450Gpa) High modulus of type HM (modulus 350 - 450Gpa), Intermediate modulus of type IM (modulus 200 - 350Gpa), Low modulus and high tensile of type HT (modulus < 100Gpa, tensile strength > 3.0Gpa), Super high tensile modulus of type SHT (modulus > 450Gpa) Carbon composite structures are typically made up with a quantity of layers called plies, stacked on top of each other (Fig. 3). Each ply needs to be bonded to the adjacent ply so it can transfer load [2]. If this bond is compromised the structural integrity is significantly reduced. It is common for the plies direction to be of a differing angle from the plies immediately above or below as this gives increased strength in the desired plane. Defects can occur in the composite as a result of use or as a result of poor quality control during manufacture.

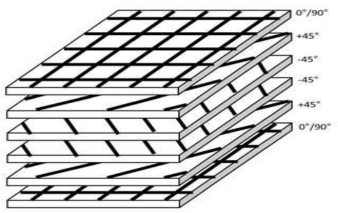

Figure 3. Plies multiaxial stacked on top of each other.

III. Common Defects of Composites Materials

There are many reasons why damage may occur but it can be certain that once there is damage it will perpetuate further. The damage of a composite and its components can roughly be attributed to one or more different stages in their life; during the manufacturing of fibers, during the construction of the composite and during the in-service life of the composite. A matrix crack typically occurs where there has been a high stress concentration or can be associated with thermal shrinkage during manufacture especially with the more brittle high temperature adhesives. Debonding occurs when an adhesive stops adhering to an adherend or substrate material. Debonding occurs if the physical, chemical or mechanical forces that hold the bond together are broken.

Delamination is a failure in a laminate, which leads to separation of the layers of reinforcement or plies. Delamination failure can be of several types such as; fracture within the adhesive or resin, fracture within the reinforcement or debonding of the resin from the reinforcement. A review of reported non-destructive testing methods for failure detection and prevention shows that many approaches require the composite structure be either taken to a test house or that relatively complex and large equipment be taken to the structure site [2]. In each case the equipment is large, requires a high level of competence and is typically expensive. Furthermore, the range of defects is wide and so requires advanced techniques to detect their presence, which leads to the development of live failure techniques in composite materials.

Details of two different applications in simple and complex structures will be explained in the following section. Firstly, a bamboo bicycle system is used as the basis for the investigation. Further research and development is being carried out to investigate and improve the performance, stability and reliability of the method. The complexity of the composite structures requires elaborate and innovative studies for proper configuration, component sizing, and control system development to fully explore the potential of this technique. Therefore, in order to explain the development of live failure technique in composite materials which uses the mesh structure, the quadcopter application within the aeronautical sector is considered.

IV. Live Failure Detection Method

There are many applications in which the suggested damage detection methods mentioned can be utilized. In this section two examples are discussed, firstly a bicycle application and quadcopter application.

A. Bicycle Application

Bike frames are vulnerable to specific kinds of stress and can be damaged in a variety of ways that is not necessarily through an impact: for example they can be damaged by low energy collisions, in transit by incorrect tightening of the roof rack, by dropping or simply hitting the curb. Structural damage can occur and go undetected as it can be invisible to the naked eye: damage on the inside with no visible damage on the outside. Riders are therefore potentially at risk of riding a bike with non visible damage and hidden flaws to the frame which could then suffer a very sudden and catastrophic failure when being ridden such as descending a mountain track at high speed. This can expose riders to dangerous situations which can result in serious injury or even death [7]. On the other hand differing opinions suggest that “for example, if a carbon frame cracks from fatigue, it shows a small crack in the paint followed by splintering and finally it will look like crushed bamboo when it fails entirely, therefore riders will have more warning of failure than any other material [8].

Figure 4. Making the connection and joints

Figure 4 shows the bamboo ends cut to connect into other bamboo tightly. Joints are then packed with epoxy resin and bamboo saw dust to allow a seamless join. A natural fibre of hemp and epoxy resin composite is wrapped around the joints to secure the bamboo to each section. A failing on any of these joints would be unwelcome when riding the bicycle, resulting in a potentially dangerous fall to the rider. The epoxy composite used on the bamboo bicycle is WEST system 105/206, the 105 being the Epoxy resin and the 206 the slow hardener. As per the technical data sheet this combination is used for general coating and bonding applications when extended working or cure times are required. It forms a high strength, moisture resistant solid with excellent bonding and barrier coating properties. It will wet out and bond to wood fibre, reinforcing fabrics, other composites materials and a variety of metals. This combination of epoxy and hardener is an ideal choice for this type of experimental bike build due to the wood / grass like structure of the bamboo frame itself, the hemp fabric reinforcement of joints and steel head tube and bottom bracket and seat post insert. Arguably the steel sections could be removed completely but allows for ease of build due to the threads required for connection of conventional bike parts such as steering with bearings, crank with pedals and seat height adjustments. It was deemed unnecessary and excessive to produce such parts from bamboo and epoxy. It is worth noting that the bamboo itself was treated with marine quality yacht varnish as the most outer layer was stripped back to allow sufficient bonding for the epoxy resin leaving exposed areas naked to the elements. It offers long term flexibility ensuring crack, ultraviolet light, salt water, blister and peel resistance that cannot be achieved with ordinary varnish.

Joint connections such as that seen in figure 4 are a typical failure point for bicycles, it is therefore of significant benefit to have damage detection at such locations. This can be achieved with the novel system proposed. At the build stage shown in figure 4 left most image, it is simple to wrap small gauge wire so that each joint has a criss-cross of conductive wire and add layers of composite in this case hemp and epoxy to fortify the joint. Further criss-cross of the conductive wire can be added between hemp epoxy layers for increased damage detection. To illustrate this white string has been used to give an example of such a make up to the finished assembly and therefore on the outermost layer to ease understanding. The string here replaces the conductive wire for visibility and understanding, it is a single piece with the 2 ends shown at the rear of the bicycle. The 2 ends are attached to simple electronics to allow for detection of current flow through the wire making a closed circuit. Due to the simplicity the power consumption is extremely low in the system and allows for continued use without the need to replace the power source. The basic electronic system including a buzzer in this instance is the size of a coin and the only considerable power drain is the buzzer itself which is only activated when the conductive wire is severed due to a fracture integral to the joint or composite. The embedded conductive wire allows for fracture detection and the buzzer alerts the user before the fracture becomes dangerous, the low energy electronics allows for continued real time monitoring of the structure. This method has been implemented in carbon fiber samples.

B. Quadcopter Application

Life threatening events are more likely to occur in aviation structures such as planes if this were to go undetected. Although arguably impossible to come to a gradual stop in such a situation, if the pilot were alerted to such detection it would be possible to 'limp home', where by the aircraft would be restricted to low G movements such as turns or deceleration. Similar risks can be expected in unmanned aircraft such as quadcopters. Although no direct threat of life is assumed due to the lack of onboard pilot, drones are increasingly flown in areas of large crowds due to their ability to carry high end photography equipment. It is no longer uncommon for high end drones to approach and exceed 10 kilos in weight, due to professional camera systems. It is therefore appreciated that the risk of life would be to the crowds immediately below should damage be undetected to one of the motor arms resulting in a complete lack of vertical thrust. Now, the live structural failure detection method will be described here with reference to the quadcopter system.

To satisfy the requirements of a live failure detection system at its most basic level one of the solutions was to incorporate a simple 'mesh system'. For this a dual option is available, in the first instance a simple conductive mesh with insulating material is embedded within the carbon plies, this thin diameter mesh was constructed of low gauge enamelled copper wire of diameter 0.22mm and applied to an inner ply within the carbon fibre make up before curing. The mesh wires are allowed to protrude past the carbon fibre as flying leads from which suitable electronics can be attached. Typically the mesh is created from a single piece of wire which gives 2 open ended flying leads, this allows for the simplest and fastest method to embed the mesh for research purposes. The mesh is not limited to a single wire and it is possible to use multiple wires with the advantage of a means of simple damage location however this introduces greater complexity and additional electronic hardware to monitor the system but still very simple (see, Figure 5). Arguably such a requirement for multiple wire strings are not necessary for simple carbon fibre constructs but it does give an element of flexibility should the designer require more accurate failure detection location or for ease of application in complex structures.

Figure 5. Test specimen with multiple wires

The mesh structure can be more easily seen with reference to the quadcopter CAD diagram below (see Figure 6). In this case the quadcopter frame is constructed of the commonly used glass reinforced epoxy laminate (FR4) sheets in printed circuit board (PCB) manufacturing. It is a composite material composed of woven fibreglass cloth with an epoxy resin binder that is flame resistant [9]

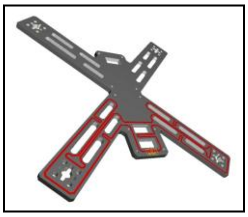

Figure 6. Enhanced NDT CAD frame

It can be seen that the front half of the quadcopter frame has no failure detection system included whereas the rear half has the basic level of failure detection incorporated (see Figure 6). This simply includes a single track of copper at 1oz which equates to approximately 0.089mm thickness. At the end of the frame are 2 pads in which suitable electronics can be connected in order to monitor the simple wire mesh has not gone open circuit as a result of physical damage. This can then be fed to the flight controller and sent back to the user by utilising the flight telemetry. It is easy to separate the wiring for each arm if damage location is to be realised giving adequate data to know which arm has sustained physical damaged. The diagram shows the failure detection method as a red line and this has been applied to the upper layer of the PCB to visually demonstrate the system, however it is possible to add this to the inner layers or bottom of the board as required by the designer. PCB's are readily available in various thicknesses, materials and layers making it quite applicable for various applications as increased thickness improves rigidity and lower thickness improves flexibility allowing lower FR4 thicknesses of 0.4mm to be curved around existing structures such as carbon fibre. It should be noted that appropriate adhesion should be applied spanning the entire board as poor contact can allow fractures in the structural material may not propagate to the FR4 failure detection board. Additional precautions should be noted as the addition of 2 different composites simply stuck together brings potential problems due to differing mechanical properties inherent with the constituent composites. For example the young's modulus of standard carbon fibre is 70GPa where as FR4 is 24GPa similarly thermal expansion coefficient variance would be of concern in temperature ranges if the individual composites were not suitably decoupled. It is deemed appropriate in certain situations but this is left to the developer to have an appropriate addition of composites for the environment and requirements of the structure. In the second instance the wire mesh can be added as an aftermarket product to existing carbon fibre structures or even non-conductive structures such as fibre glass. This would typically be applied as a single unit as fixing a mesh to structures can be labour intensive. It is therefore more appropriate to have the mesh already incorporated on an adhesive sticker and applied. The benefit of the mesh structure is that the electronic detection electronics is extremely simple and requires very low real estate and its operating power is almost negligible making it ideal in portable applications and can even be powered by energy harvesting methods such as vibrations, solar, wind and the like, this will obviously incur additional constraints in terms of size and cost. The detection principle is a simple case of current flow through the conductive copper mesh, when damage occurs as a result of a crack or over flex then the conductive wire is severed and the user is alerted to the fault. Such a simple solution has its draw backs and these are the detection rate to damage. In lab tests on embedded mesh structure only ~50% of flexural test fractures were detected before a catastrophic failure event. Analysis shows that the reason for this was down to one of two reasons; either the mesh wire was not present in the fracture line or that the fracture width was not great enough to be detected. The image below (see Figure 7) is taken at x200 magnification:

Figure 7. Tapering of conductive mesh

It can be seen that the enameled copper wire has stretched with the fracture during flexural testing, ideally this would have sheared and broke at the same rate as the carbon fiber. To improve the system it is suggested that the detection material to have a similar Young's modulus to that of the material under test and that a suitable pitch be used between the mesh to meet that of the application. However this method has proved an extremely low cost and portable method for additional safety where there was none. The application has been used in low cost multirotor (quadcopter) frames in particular the motor arms where damage could be incurred from in-flight collisions.

V. Conclusions

In this paper a novel live failure detection and critical failure prevention mechanism for composite materials is discussed with reference to a quadcopter system. Firstly a bicycle system is studied and used as the basis for the investigation. Further research and development is carried out on a quadcopter system to investigate the applicability of the live structural failure detection method. The preliminary results indicated that the method may be used to prevent critical failures in such systems.

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