A Novel Live Failure Detection Method for Composite Material Systems

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***Abstract*—This study presents an analysis of composite structures and fault detection mechanisms from the viewpoint of aerospace and sports applications. This study aims to introduce a novel live failure detection and critical failure prevention mechanism, which is primarily used for composite materials. First, a bicycle system was studied and used as a basis for this investigation. Further research and development were 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 used to prevent critical failures in such systems when compared with existing systems.**

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

I. Introduction

Composite materials are made up of two or more materials with different properties that are combined to obtain 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 in comparison with the individual constituent materials. Nowadays, advanced materials and the development of health monitoring solutions have gained significant attention from several research groups [2, 3]. However, it is important to note that despite the advances in materials, there are only a few health monitoring solutions available for use [2]. Super materials such as carbon fibers are becoming increasingly popular owing to their inclusion in composite materials; the gradual reduction in production costs over the recent years has allowed their widespread use. Previously, such materials were only viable in high-end sectors such as aviation due to their high cost, but these materials have now trickled down to products that are easily affordable, such as a bicycle.

Failure detection methods for composite material systems are currently attracting significant attraction in the field of composite material [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 by giving essential early indication and warning. Such an approach gives an alternative direction in comparison with the off-line non-destructive failure detection methods. In this paper, the details of a live failure detection technique are discussed. Additionally, a brief overview of the characteristics of composite materials and their common defects is also presented. Finally, various applications and conclusions are presented.

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II. Composite Materials Structures

Composites are formed using the principle of combined action. The basic idea is that for any 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. The two main categories of constituent materials are matrix and reinforcement. At least one portion of each type is required for a composite. As such, the reinforcement are the fibers 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, which is typically a form of resin, keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack bonds the reinforcement so that applied loads can be effectively transferred [5]. Most of the composites currently available in the market are produced using a polymer matrix material, which is known as a resin. 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 the adhesives and are commonly utilized in most demanding applications, such as vehicles, planes, boats, and sporting equipment. It is a petroleum-based adhesive that is free of solvent, has superior bonding properties, extreme durability, and high thermal and chemical resistance. Epoxy resins contain an 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 and epoxy resin is outlined below.

Bond strength: The relative strength of epoxy resin is 2000 lbs per square inch, whereas it 500 lbs per square inch for polyester resin.

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

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

Odor: Polyester resin has an unpleasant odor to even after curing, although it sets much faster. Epoxy resin has much less odor; nevertheless, suitable breathing apparatus should be worn while working with any type of resin.

Shelf life: Epoxy products have a far greater shelf life of several years with no loss in potency provided the resin and hardener are not contaminated or mixed. Polyester is much more fragile over time. The specifications for each type, such as exact characteristics and properties, can be found in the manufacturer's technical data sheet.

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

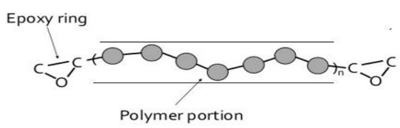

Figure 1. The epoxy structure.

Epoxy resin (Fig. 2) is also called "epoxy" or "polyepoxide" and is the second most widely used family of thermosets copolymer (after polyester resins) [6].

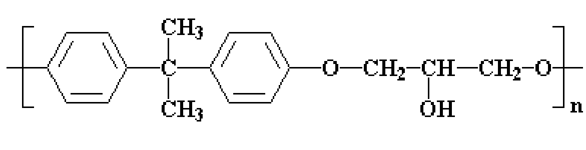

Figure 2. Epoxy resins.

The aromatic structure of the resin implements a strong hydrophobic performance when compared to other resins, such as polyurethanes or acrylics, which were developed at the same time [5]. Therefore, the advantages of epoxy systems are that they have excellent adhesion properties and low shrinkage on cure (typically > 3%). Furthermore, they have excellent resistance to water, heat, and chemical, they are versatile, and do not release volatiles upon curing.

Carbon fibers are classified by the tensile modulus known as Young's modulus, which quantifies the stiffness of an elastic material. Young's modulus predicts the extent to which the 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 fiber. When a material's mechanical properties are the same in all directions, it is known to be isotropic. Carbon fiber is anisotropic because it has a higher Young's modulus when the force is parallel to the fibers. Carbon fibers can be grouped into ultra-high modulus of type UHM (modulus > 450 Gpa), high modulus of type HM (modulus 350–450 Gpa), intermediate modulus of type IM (modulus 200–350 Gpa), low modulus and high tensile of type HT (modulus < 100 Gpa, tensile strength > 3.0 Gpa), and super-high tensile modulus of type SHT (modulus > 450 Gpa). Carbon composite structures are typically made up of layers called plies, which are stacked on top of each other (Figure 3). Each ply needs to be bonded to the adjacent ply so that 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 at a differing angle from the plies immediately above or below because this gives increased strength in the desired plane. Defects can occur in composite as a result of use or as a result of poor quality control during manufacture.

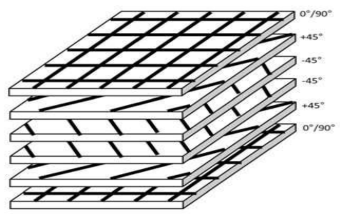

Figure 3. Plies multi-axial stacked on top of each other.

III. Common Defects of Composites Materials

There are several reasons for the occurrence of damage; however, it is certain that once damage occurs, it will perpetuate further. The damage to a composite and its components can roughly be attributed to one or more different stages in their life, which are 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 when 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 the 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 the reported non-destructive testing methods used for failure detection and prevention shows that many approaches require the composite structure to 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 requires advanced techniques to detect their presence, which leads to the development of live failure techniques in composite materials.

Two different applications in simple and complex structures will be explained in the following section. First, a bamboo bicycle system was 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, to explain the development of live failure techniques in composite materials, which use the mesh structure, the quadcopter application within the aeronautical sector was considered.

IV. Live Failure Detection Method

There are many applications where the proposed damage detection methods can be utilized. In this section, two examples of such applications are discussed: first a bicycle application and then quadcopter application.

A. *Bicycle Application*

Bike frames are vulnerable to specific kinds of stress and can be damaged in various ways, which are not necessarily by 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 because they are invisible to the naked eye. Therefore, riders are at a potential risk of riding a bike with non-visible damage and hidden flaws in the frame, which could result in a 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 injuries or even death [7]. On the contrary, differing opinions suggest that if a carbon frame cracks from fatigue, it shows a small crack in the paint followed by splintering and finally resemble 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 tightly to other bamboo. The joints are then packed with epoxy resin and bamboo saw dust to allow a seamless join. A natural fiber of hemp and epoxy resin composite was wrapped around the joints to secure the bamboo to each section. A failure in any of these joints would be dangerous while riding the bicycle, resulting in a potential danger for the rider. The epoxy composite used on the bamboo bicycle was the WEST system 105/206, 105 being the epoxy resin and 206 being 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 and moisture resistant solid with excellent bonding and barrier coating properties. It will wet out and bond to wood fiber, reinforcing fabrics, other composites materials, and a variety of metals. This combination of epoxy resin and hardener is an ideal choice for this type of experimental bike build due to the wood- or grass-like structure of the bamboo frame, hemp fabric reinforcement of the joints and steel head tube, and the 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 the 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 because most of the outer layer was stripped back to allow sufficient bonding for the epoxy resin leaving the exposed areas naked to the elements. This offers long-term flexibility ensuring crack, ultraviolet light, salt water, blister, and peel resistance that cannot be achieved with ordinary varnish.

Joint connections, as shown in Figure 4, are a typical failure point for bicycles and are, therefore, of significant benefit for damage detection at such locations. This can be achieved with the proposed system. During the build stage, as shown in the left most image of Figure 4, it is simple to wrap small gage wire so that each joint has a criss-cross of conductive wire and add layers of composite to fortify the joint, which in this case are hemp and epoxy. A further criss-cross of the conductive wire can be added between the hemp epoxy layers for increased damage detection. To illustrate this, white string was 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 two ends shown at the rear of the bicycle. Both the ends are attached to simple electronics that allow the detection of current flow through the wire, hence making it a closed circuit. Owing to its simplicity, the power consumption is extremely low in the system and allows for its continuous use without the need to replace the power source. The basic electronic system, including a buzzer at this instance, is of the size of a coin and the only considerable power drain is the buzzer itself, which is only activated when the conductive wire is affected due to a fracture integral to the joint or composite. The embedded conductive wire allows for the fracture detection and buzzer alerts the user before the fracture increases further. The low energy electronics allow 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 these were to go undetected. Although, it is impossible to gradually overcome such 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 an onboard pilot, drones are increasingly flown in areas with dense population owing to their ability to carry high-end photography equipment. These days, high-end drones can weigh more than 10 kg because of the professional camera systems mounted on them. It is, therefore, appreciated that the risk of life will be to the crowd immediately below should damage be undetected to one of the motor arms resulting in a complete lack of vertical thrust. Therefore, the live structural failure detection method will be described 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, i.e., at the first instance, a simple conductive mesh with insulating material is embedded within the carbon plies. This thin diameter mesh was constructed using low gage enameled copper wire with a diameter of 0.22 mm and applied to an inner ply within the carbon fiber make up before curing. The mesh wires are allowed to protrude past the carbon fiber as flying leads from which suitable electronics can be attached. Typically, the mesh is created from a single piece of wire, which gives two open-ended flying leads, which 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 for simple damage location, however, this introduces greater complexity and additional electronic hardware to monitor the system, but it is still very simple (Figure 5). Arguably, such a requirement for multiple wire strings is not necessary for simple carbon fiber 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. The test specimen with multiple wires.

The mesh structure can be more easily seen with reference to the quadcopter CAD diagram, as shown in Figure 6. In this case, the quadcopter frame is constructed using glass-reinforced epoxy laminate (FR4) sheets, which are commonly used in the manufacturing of printed circuit boards (PCBs). It is a composite material made up of woven fiber glass cloth with an epoxy resin binder, which is flame resistant [9].

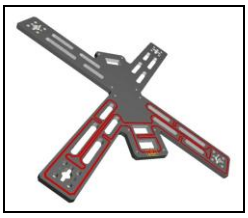

Figure 6. The enhanced NDT CAD frame.

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 (Figure 6). This simply includes a single 1 oz track of copper, which equates to a thickness of approximately 0.089 mm. At the end of the frame, there are two pads in which suitable electronics can be connected to monitor that the simple wire mesh has not become an open circuit as a result of physical damage. This can then be fed to the flight controller and sent back to the user by utilizing the flight telemetry. It is easy to separate the wiring to each arm for the realization of the damage location, which will give adequate data to identify as to which arm has sustained physical damage. 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. PCBs are readily available in various thicknesses, materials, and layers making it quite applicable for various applications as an increased thickness improves the rigidity and a lower thickness improves the flexibility, allowing lower FR4 thicknesses of 0.4 mm to be curved around existing structures, such as carbon fiber. It should be noted that appropriate adhesion should be applied spanning the entire board because poor contact can allow fractures in the structural material that may not propagate to the FR4 failure detection board. Additional precautions should be taken when the addition of two different composites simply stuck together brings about potential problems due to the differing mechanical properties inherent with the composite constituents. For example, the Young's modulus of standard carbon fiber and FR4 is 70 and 24 GPa, respectively, and a similar thermal expansion coefficient variance will be of concern in certain 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 use appropriate composites for the environment and requirements of the structure. At the second instance, the wire mesh can be added as an aftermarket product to existing carbon fiber structures or even non-conductive structures such as fiberglass. This would be typically applied as a single unit because fixing a mesh to structures can be labor intensive. It is, therefore, more appropriate to have the mesh already incorporated on an adhesive sticker, which is then applied. The benefit of the mesh structure is that the electronic detection is extremely simple and requires very low real estate. Its operating power is almost negligible, which makes it ideal in portable applications and can even be powered using energy harvesting methods, such as vibrations, solar, and wind, however, 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 drawbacks and these are the detection rate to damage. In laboratory tests based on the embedded mesh structure, only ~50% of the flexural test fractures were detected before a catastrophic failure event. The analysis shows that the reason for this was down to one of the two reasons, either the mesh wire was not present in the fracture line or that the fracture width was not sufficient enough to be detected. The image in Figure 7 was taken at 200× magnification.

Figure 7. Tapering of the conductive mesh.

It can be seen that the enameled copper wire was stretched with fracture during the flexural testing, which would have ideally sheared and broke at the same rate as the carbon fiber. To improve the system, it is suggested that the detection material should have a similar Young's modulus to that of the material under test and that a suitable pitch is used between the mesh to meet that of the application. However, this method has proved to be an extremely low cost and portable for additional safety. The application has been used in low cost multirotor (quadcopter) frames, particularly in 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 quadcopter and a bicycle systems. Initially, a bicycle system was studied and used as the basis for the investigation. Further research and development was carried out on a quadcopter system to investigate the applicability of the live structural failure detection method. The preliminary results indicate that the method may be used to prevent critical failures in such systems.

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