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Comparative analysis of failure detection methods of composites materials' systems

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ABSTRACT
This paper presents a review and analysis of current non-destructive failure detection methods of composite materials and a brief outline of the build of a bamboo bicycle which has been used as a development platform and test bed for the initial development of a novel and practical non-destructive failure detection solution, which has future compatibility for carbon-fibre (CF)-based bicycles. The paper begins by presenting the current market condition of composite materials and in particular, CF and CF-reinforced plastic, and then follows onto failure modes and proceeds to investigate a comprehensive range of failure detection methods.

1. Introduction

The interest in advances in materials and the development of health monitoring solutions has nowadays gained considerable attention from several researchers (see, e.g. Bowkett, Thanapalan, & Williams, 2016; Cheng & Tian, 2012; Luo, Wang, Wei, Alsaadi, & Hayat, 2016). The motivation of the paper is to observe why despite the advances in materials there are little (if any) health monitoring solutions available when in use. Super materials such as carbon fibres (CFs) are becoming increasingly popular due to their inclusion in composite materials; the gradual reduction in production costs 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.

With a focus on CF, it is necessary to review current failure detection methods and determine if any of these methods have the potential to be used on lower cost consumer products. This will determine if there is a potential technology gap that if filled will have a significant advantage to consumers to determine the state of health of equipment such as bicycles, golf shafts, archery equipment and the like. For this to be successful the solution must be cost effective, require low inspector knowledge and skill, and be readily available.

CF and CF composites are widely used in many industrial applications, including aerospace and sport applications (Wang & Chung, 2006; Wang, Shui, Fu, & Chung, 1998). In the case of sporting applications, there are many varieties of specialized requirements ranging from golf shafts, fishing rods, tennis rackets and hockey sticks to bicycle frames (Muto, Yanagida, Nakatsuji, Sugita, & Ohtsuka, 1993; Wang, Fu, & Chung, 1999).

Originally developed for high-temperature-moulded plastic components on missiles, CF was developed in the 1950s. The CFs were manufactured by heating strands of regenerated cellulose known as Rayon until carbonized; however, this process was inefficient and only contained about 20% carbon and as a result had low strength and stiffness. During the early years of the 1960s the process was developed using polyacrylonitrile, which contained approximately 55% carbon and therefore much more desirable properties. The 1970s led to the introduction of petroleum pitch derived from oil processing; these fibres are approximately 85% carbon and had great flexural strength. This was greatly let down by limited compression strength so was not widely accepted (Ebbesen, 1996). Today, about 90% of CFs produced are polyacrylonitrile (known as PAN) and the remaining 10% are rayon or petroleum pitch.

The CF and CF-reinforced plastics (CFRPs) are the key elements in advanced composites materials (Irving & Thiagarajan, 1998). The global CF market was worth USD $2.08 Billion in 2014, registering a compound annual growth rate (CAGR) of 9.1% between 2015 and 2020. Additionally, the global CFRP market was valued at USD $20.29 Billion in 2014, and is projected to register a CAGR of 9.9% between 2015 and 2020 (Bowkett et al., 2016). The European Carbon Fibre market by volume was

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14.49 thousand metric tons in 2013, and is projected to reach 29.37 thousand metric tons in 2019, witnessing the growth at a CAGR of 12.5% for the forecast period. This region covers about 28% of the global CF market.

Major demand in Europe is projected to be from the automotive, aerospace and defence industries. Germany dominates the European market as the country is home to many leading automotive companies (Moore, 2015). The market for CFRP is segmented on the basis of applications that include industries such as aerospace defence, wind energy, automotive, sporting goods, civil engineering, pipe and tank, electronics and electrical, marine, and others (Park, Okabe, Takeda, & Curtin, 2002; Seo & Lee, 1999). Over the last 15 years CF bike frames have taken the largest part of the biking market, surpassing both steel and aluminium. In 1996 a 1.6 kg frame was considered state of the art; it is now down to less than a kilogram (Ogi & Takao, 2005; Todoroki, Suzuki, Mizutani, & Matsuzaki, 2010).

The trend for cycling in the UK is for market growth based on a number of factors ranging from improved attitudes among consumers to pay more for a quality bicycle, to the positive economic outlook and promised investment in cycling infrastructure (Wang et al., 1999). According to Ian Drake CEO of British Cycling (the national governing body for cycling in the UK) there are 2 m people cycling every week for sport, excluding commuters, British Cycling had 15,000 members in 2005, which had risen to 140,000 in 2015. The number of under-18's who ride competitively increased from under 1000 to 14,000 (Moore, 2015). This is an enormous benefit to the UK economy and the cycling business industry. It is important to note that, this is key evidence to the increasing global demand for CF and the forecast for 2020 is almost double (see Figure 1).

'All-in-One' mass production carbon fibre bicycle companies play a key role in the production of the bicycles. These companies are few, but tend to be some of the biggest and most established brands in the industry. All-in-one mass producers do everything from their own
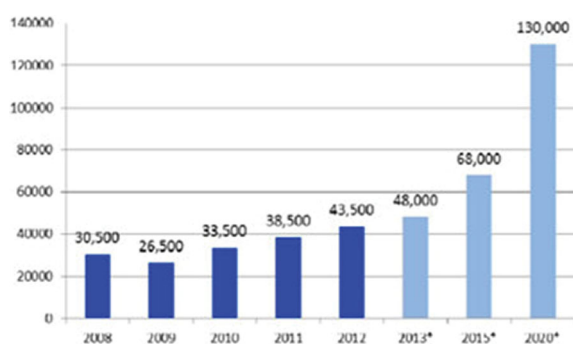
engineering and design through to actual carbon moulding and finish work in-house. However, instead of trying to maximize economies of scale, like the mass production companies, these builders employ this approach to have as much control over the end result as possible. Specialty builders tend to focus on maximizing fit, ride tune ability, quality, durability, and finish options (Suzuki, Todoroki, Mizutani, & Matsuzaki, 2011).

Design and engineering bicycle companies: These companies design, engineer and market their own products, but have them built by a sub-contractor (regularly in Asia) to their specifications; Cervélo, KUOTA, Felt, Orbea and Specialized are good examples of brands that frequent this approach. The level of quality control and attention to detail is determined by what factory they subcontract with, how much the company invests in supervising the production of their frames, and the quality of their engineering and processes and their relationship with their production factory (Bowkett et al., 2016; Moore, 2015).

Marketing and distribution companies: The majority of the carbon bikes being ridden today come out of a relatively small number of mass production factories in Asia. In addition to building frames for the design and engineering companies, these companies also have deep catalogues of the frame designs they have sketched out or prototyped. A marketing or distribution company will purchase or license these designs and market them under their name. These firms often have little to nothing to do with the design, production, testing, materials, manufacturing, or testing of the product; they are responsible for distribution, marketing and sales of the product only. In some cases, the same frame design can be found under two or more brand names. Formosa Plastics Corporation, SGL Carbon, Toray Industries Inc., Toho Tenax, Zoltek Companies Inc., Hexcel Corporation, and Cytec Industries are some of the major manufacturers of CF.

Many modern bike frames are made of CFRP, which has several benefits: lightweight and strong, relatively inexpensive, gives a more stable and comfortable ride, and offers an array of design options such as not confined to round tubes welded together (Sohn et al., 2011).

In the present study, at first, the carbon composite structures and the common defects that occur with carbon and CF-reinforced materials are described. In Section 3, possible methods are described. The complete system analysis is presented in Section 4. Finally, concluding remarks and discussions are presented.

2. Carbon composite structures

CFs 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

Figure 1. Global demand for CF (Holmes, 2013).

a material bends or extends under tension or shortens under compression, the higher the Young's modulus the stiffer the material. It is expressed as a ratio of stress over strain (Hayden, Moffatt, & Wulff, 1965). The Young's modulus E is given by

$$E = \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0\Delta L}, \tag{1}$$

where E is the Young's modulus (modulus of elasticity), F is the force exerted on an object under tension, A_0 is the actual cross-sectional area through which the force is applied, ΔL is the amount by which the length of the object changes and L_0 is the original length of the object.

It is worth noting that the Young's modulus is not consistent across all orientations of a material and this is true of CF. When a material's mechanical property is the same in all directions, it is known as isotropic; CF is anisotropic as it has a higher Young's modulus, when the force is parallel to the fibres. CFs 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) (Kiron, 2017).

Carbon composite structures are typically made up with a quantity of layers called plies, stacked on top of each other (Figure 2). Each ply needs to be bonded to the adjacent ply so it can transfer load (Tian, Yu, & Leckey, 2015). If this bond is compromised the structural integrity is significantly reduced. It is common for the plies to direction to be of a differing angle from the plies immediately above or below as this gives increased strength. Defects can occur as a result of use or as a result of poor quality control during manufacture (Cheng & Tian, 2012).

2.1. Faults and defects

There are many reasons why damage occurs and it can be certain that once there is damage that this 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 fibres, during the construction of the composite and during the in-service life of the composite (Bowkett et al., 2016). 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 laminated, often a composite, 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. Figure 3 shows matrix cracks, broken fibres, debonding and delamination (Unnporsson, Jonsson, & Runarsson, 2004) and other defects explained later.

A void or blister is a pore that remains unoccupied in a composite material. A void is typically the result
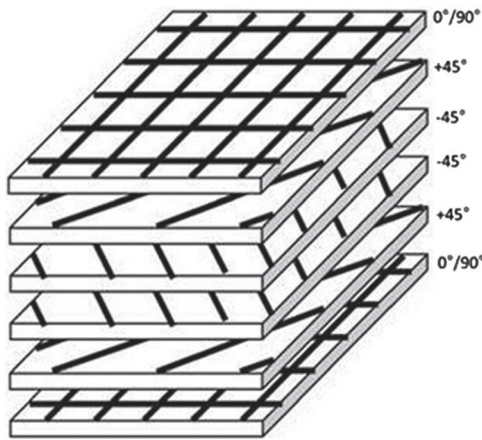

Figure 2. Plies multiaxial stacked on top of each other.
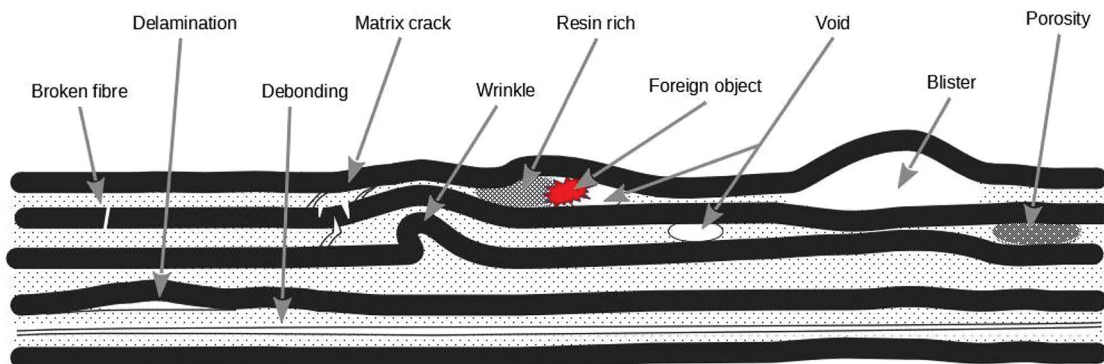

Figure 3. Common defects of CFs.

of an imperfection from the processing of the material and is generally deemed undesirable. Because a void is non-uniformity in a composite material, it can affect the mechanical properties and lifespan (McEvoy & Correll, 2015). Blisters are generated in the outermost layers. Porosity can be caused by volatile entrapment during the curing of the resin.

Wrinkles are common when adding new layers; it is significant to eliminate them as they can weaken the composite (Zhang & Hartwig, 2002). The inclusion of foreign bodies in the composites (see Figure 3) can include backing film, grease, dirt, hair to finger prints, which can lead to areas rich or deprived of resin (Adams & Cawley, 1988).

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 invisible damage and hidden flaws to the frame which could then suffer a very sudden and catastrophic failure when being ridden under stress 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 (Viets, Kaysser, & Schulte, 2014). On the other hand, other opinions suggest that

> 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. (Sebastian et al., 2014)

For safety reasons and as CF bikes are a personally expensive investment, riders can have their bikes tested for structural defects, for example, after a crash, impact or when buying a second-hand bike, using Non-Destructive Testing methods (He, Tian, Pan, & Chen, 2014; Li et al., 2015). Once a defect has been identified it is often possible to repair the bike and there are numerous CF bike repair specialists available in the market.

In this section, carbon composite structures and associated defects that occur with carbon and CFRP are discussed. Section 3 will describe the possible methods to overcome the problems associated with carbon and CFRP.

3. Research methodology

To avoid the occurrence of a catastrophic failure due to manufacturing defects, impacts or fatigue damage, critical structural CFRP components are regularly inspected using various non-destructive testing methods, including, pulse thermography, radiography, ultrasonic inspection and acoustic methods.

3.1. Visual inspection

The most basic type of non-destructive testing for composites (Gholizadeh, 2016) arguably requires no knowledge or training, an easy minimalistic test that can be performed by anyone as a routine maintenance procedure. However this method of testing can be greatly improved with a little knowledge, typically the visual inspector should be aware of certain parameters and conditions of the CF as to not incur additional damage or to overlook existing damage to the composite structure. Care should be taken during the visual inspection as not to excessively bend or flex the CF as it is tempting to physically twist and flex any suspected areas beyond its performance envelope. The inspector should carefully clean the CF part or area to be inspected with a damp cloth, being aware of the possibility of exposed fibres as these can be extremely stiff and penetrate the skin with ease. Once cleaned, any visual damage will be revealed and careful attention should be paid to impact damage such as scratching, gouges, fractures and exposed frayed fibres. A quick and easy method for detecting exposed fibres is to run a dry cloth over the surface as the fibres become snagged easily, which is immediately apparent to the inspector.

3.2. Flex test

Progressing on from the visual inspection, this method also requires no specialized equipment but a feel for the structure on test would prove beneficial; similarly this simple test can be performed as part of routine maintenance. For example, CF arrows can be flexed by hand; if damage is present it is not uncommon to hear the friction of the fibres rub across each other. If a keen feeling for the rigidity of the structure under test is known, the inspector can intuitively gauge when a structure is not right. On larger structures such as a push bike simply stressing the structure can be enough to determine if there is damage; this is best practised when stationary under careful loading. For example the seat post of a bicycle frame may bow out of normal operating alignment or it may feel more spongy than usual. Again this method is best if the inspector has experience with the structure but can be obvious to novices.

3.3. Tap test

The simplest test that includes the use of a tool, typically a coin or similar as they are readily available, but tap

hammers do exist. In the instance of a bicycle for example, the coin would literally be 'tapped' on the frame, the inspector would listen for any audible change in pitch and resonance as the coin moved along the frame. British Airways use the Mitsui Woodpecker automatic tap tester, which takes out the human error and can be used in loud environments (Cunningham, 2013). Things become a little more complicated when structures are complex such as bicycles as varying tube thicknesses are utilized to reduce weight and lugs are necessary to join two or more of the frames tubes. The inspector must evaluate the sound as to if there is a defect present; this is relatively effortless in a single tube as any changes in the integrity will alter the sound, and therefore if the sound changes as the coin is moved along the tube it can be reliably alleged that damage is present. However applying the same principle to a full bicycle frame, the inspector must determine if damage is present as the coin is moved closer to a lug for example as this is going to alter the tubes' vibration. Generally a dull thud can be taken to be damaged; this is easily recognized in practice. Regardless this is a proven technique that works but is highly operator-dependant (Smith, 2009), a proficiently trained inspector will be able to identify regions of de-bonding, de-lamination and poor cure that are not identifiable by visual inspection alone (Greene, 2014).

3.4. Dye penetrant

This method of inspection takes the first step of pre cleaning the test material; this is exceptionally important as any cracks must be thoroughly clean. The penetrant is then applied to the material which is usually red-coloured low-viscosity oil. The penetrant's high surface wetting capability easily penetrates into the cracks and defects by capillary attraction, and after several minutes of dwell time the material is carefully rinsed with water, which removes surface penetrant but leaves it in the crack or

defect. The test material is dried before a developer is applied. The developer is a fine grain white powder that is suspended in a liquid and it forms an even coating on the test subject's surface. It draws penetrant from the crack to the surface, which clearly reveals the red dye on the white surface and therefore revealing the location of both cracks and defects. Almost all materials can be detected using this method that is simple to perform, requires no knowledge and is cost effective. However, this can only reveal surface defects and does not give details of depth of defects, it can be difficult to test rough surfaces. A similar method uses fluorescence penetrant, which typically uses a dip tank for the application of fluorescent penetrant.

3.5. Pulse thermography

Infrared Thermography is an advanced Non-Destructive Examination (NDE) method that is becoming popular due to its ability to inspect large areas in short times. (Sharath, Menaka, & Venkatraman, 2013) The duration can range from a few milliseconds for high thermally conductive materials such as metals to a few seconds for low thermally conductive materials such as plastics, graphite epoxy composites. Such low-heating durations also prevents damage to the specimen under test; typically the increased heat is only a few degrees above the initial specimen temperature. However as it uses infrared technology, it is not possible to penetrate at depths more than a few millimetres.

Thermal imaging cameras can be used to detect material failures in bicycles (He et al., 2014). The bike frame is mounted on a rotary table. A thermal impulse is triggered and light energy released onto the bike frame. The heat penetrates the frame and a thermal imaging camera is used to trace the heat flow. The thermal data generated is then analysed on a computer (Figure 4). Differences in the heat flow can indicate material defects. Simply
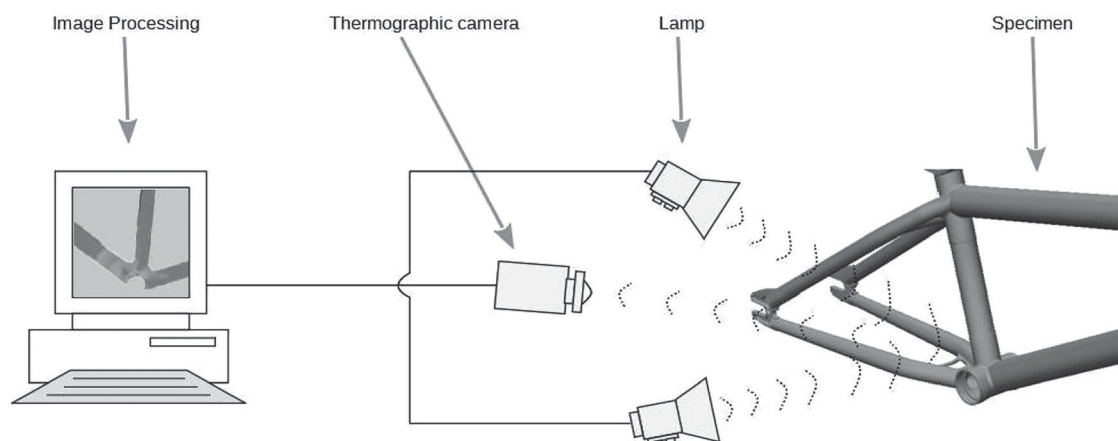

| Image Processing | Thermographic camera | Lamp | Specimen |

Figure 4. Principles of thermographic inspection.

Figure 5. A broken frame showing signs of delamination.

put the specimen is briefly heated and the temperature decay curve is recorded. A broken frame showing signs of delamination is shown in Figure 5.

3.6. Radiography

Radiography is an NDE method that uses X-ray and Gamma-ray for detecting internal imperfections or defects. Figure 6 shows an example of a setup to take an X-ray on a bicycle frame.

Radiography works on the principle of absorption of the penetrating radiation by the intervening material. The differential absorption due to variation in density (or, due to presence of flaws and defects in the material) produces latent images on the radiographic film. With radiographic examination the material is exposed to a homogenous ray from a low voltage X-ray tube, while a negative film is positioned behind the material to be examined. After development of the film, thickness and density differences (i.e. material imperfections) will show as blackness differences. The radiograph in Figure 7 shows damage in a CFRP bicycle component.

3.7. Ultrasonic inspection

Ultrasonic inspection works by sending a high-frequency sound wave into the part and then measuring what sound comes back (Figure 8).
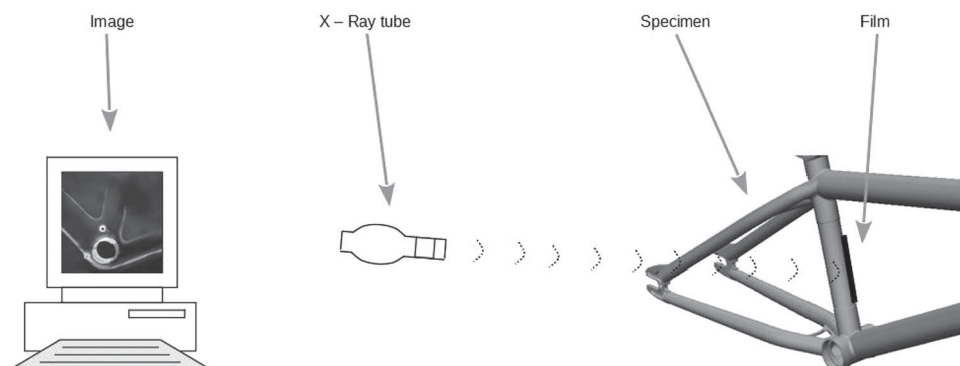

Figure 7. Damage in a CFRP bicycle component (Ning, 2015).

The amount of energy transmitted or received and the time the energy is received are analysed to determine the presence of flaws (Li et al., 2015). Changes in material thickness, and changes in material properties can also be measured.

Disadvantages of this method are that the surface must be accessible to probe and couplant, requires specialized equipment and knowledge, surface finish and roughness can interfere, thin parts can be difficult to inspect, linear defects oriented parallel to the sound beam may go undetected and reference standards are often needed.

3.8. Acoustic method

The acoustic emission method refers to the generation of transient elastic waves that are created by sudden redistribution of stress in a material. When the material is subjected to a change in pressure, load or temperature localized sources trigger the release of energy. The energy released is in the form of stress waves which propagate through the material and to the surface. It is possible to observe such stresses with suitable sensors mounted on the material. In composite materials it is feasible to monitor for matrix cracks, fibre breaks and debonding (Bowkett et al., 2016). The Acoustic method is
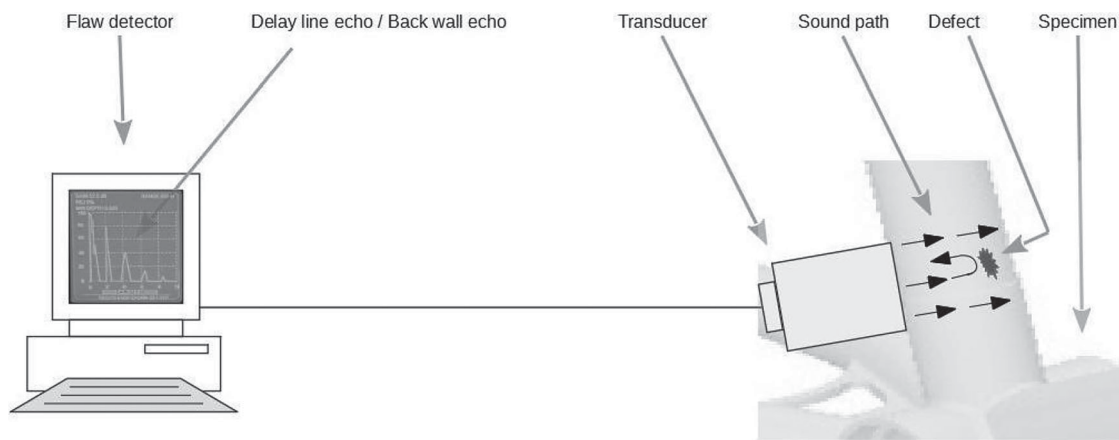

Figure 6. Setup to produce an X-ray on a frame.

Flaw detector　　　Delay line echo / Back wall echo　　　　Transducer　　　Sound path　　Defect　　Specimen

Figure 8. Ultrasonic testing.

a structural health condition monitoring method which can be used for continuous monitoring of in-service CFRC structural components and help increase confidence regarding the remaining in-service lifetime if a fatigue limit cannot be defined easily (Ning, 2015). However tests are best performed if the loading history of the structure is known and it can be subject to extraneous noise.

3.9. Eddy current testing

As the name suggests, eddy current uses a circular current to detect the presence of cracks, surface breakings and variations in the composition of materials as well as identifying the material itself. It is an electromagnet testing which is one of the oldest testing methods (De Goeje & Wapenaar, 1992). When an alternating current is passed through a coil a changing magnetic field is generated. If the coil is placed near a conductive material the magnetic field will induce a circular current or eddy current. It is capable of detecting cracks, corrosion damage as well as measurement of material thickness, coating thickness and conductivity for identification of materials and damage from overheating and so is useful for the monitoring of heat treatments. Its benefits include good sensitivity to small cracks and other defects on and below the surface layer. Portable equipment with minimal material preparation times and complex parts can be inspected (He et al., 2014). However its limitations are that only electrically conductive materials can be inspected, the surface must be accessible to the probe, an excellent level of inspector training and experience is required, rough finishes can interfere with the test, depth of penetration is limited and it is not suited towards large area testing. At its simplest this testing method setup requires an alternating current source, a testing coil and a display.

3.10. Optical fibre testing

Arguably intended for health monitoring or in situ monitoring of material strain and temperature (Murukeshan, Chan, Seng, & Asundi, 1999), it would be incomplete not to include distributed sensing method in this article as it is applicable to composite materials. CF failure modes can be both latent and extensive; integration of the optic fibre sensor into the matrix of the material offers the solution to health assessment, maintenance and management of the integrity of the structural composite (Techbriefs Media Group, 2010). There are many options technically when it comes to fibre optic sensing, but there are two basic principles of measurement: optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR). The main advantage of OFDR method over the OTDR method is the higher spatial resolution and sensitivity (Huttner et al., 1999).

The use of optical fibres and related components has seen a huge increase over the past two decades; this holds especially true in the telecommunications sector, which has led to an increase in performance whilst reducing costs. Due to huge investments, OTDR has now become the industry standard for telecom loss measurements. The operating principles of OTDR is similar to that of radar where a transmitted pulse is monitored for the reflection, and the time delay is used to determine to location of an event. The OFDR method can again be split into two main categories: incoherent OFDR (I-OFDR) and coherent OFDR (C-OFDR), which have trade-offs in range, resolution, speed, sensitivity and accuracy (Soller, Gifford, Wolfe, & Froggatt, 2005).

The methods described so far are largely used to analyse the failure and test for damage after usage. Unless visual damage is present, it is not reassuring for the user to rely on the tap test or flex test, as this is very subjective testing giving no quantifiable data as to if damage is

present. Therefore it can be seen that the identification of fractures in the material is achieved in a lab environment where the material is either X rayed or heated and monitored through specialist cameras. It is important to point out that these methods of testing require the test subject to be transported to an offsite location and then assessed with one of the techniques. Both of which are time consuming and can be extremely expensive in comparison to the cost of the bicycle itself. The biggest downside associated with these methods is that damage caused whilst using the product goes unidentified until taken to one of the test labs.

Serious injuries are common in cycling whereby the carbon frame becomes damaged and the cyclist continues to use the bicycle unaware. Continued use with compromised structural integrity can result in catastrophic failure where the handle bars and front wheel sheer away from the bicycle, detaching the head tube and the rider falls head first onto the road commonly with other road users, putting not just the rider but others in danger. Therefore, it is very important to act against these problems as early as possible.

The bicycle studied in this paper is the bamboo bicycle at the Centre for Automotive & Power Systems Engineering, University of South Wales. Here we describe the build of a bamboo bicycle shown in Figure 9. This bamboo bicycle provides the basis for future design, analysis and control design of CF bicycles more generally. It is expected that the system analyses and techniques applied to the bamboo bicycle may be easily transferred to the carbon bicycle. The bicycle was built from bamboo, steel only for the head tube to locate the steering handles, and bottom bracket, epoxy resin and hemp sheet cut is used for the composite to join individual parts. Figure 10 shows the raw materials of the bicycle and drawing of the frame dimensions.

These raw materials and the design are used to develop the bamboo bicycle. Figure 11 shows the bamboo ends cut to connect into other bamboo tightly.

Figure 9. The completed system (bamboo bicycle).

Figure 10. Raw materials of the bicycle and drawing of the frame dimensions.

Figure 11. Making the connection and joints.

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 bamboo bicycle system is used as the basis for the investigation. Research and development is being carried out to investigate and improve the performance, stability and reliability of the bicycle. 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 technology. A quantitative analysis was performed to determine the best topologies for use in this study, based on simplicity, efficiency, mass and cost. Current research is ongoing to assess the true quality of the technique applied to the bamboo bicycle; if the results are satisfactory and performing better than the conventional methods, this method will be applied to the carbon bicycle. Currently the bamboo bicycle has almost a thousand riding miles logged with no signs of damage or fatigue.

4. Discussion and concluding remarks

In this paper, a brief review and analysis of failure detection methods of composites materials systems and development and application of a bamboo bicycle is presented. The review is mainly focused on CF and CFRF together with a bamboo bicycle development and its configurations, topologies and control strategies are also discussed. Furthermore, in order to have an understanding as to appreciate the methods of failure detection and the equipment and skills required to successfully determine the health state of CF structures and why they could fail, a brief review and discussion of the defects and faults of CF is presented in this paper.

Analysing existing failure detection methods of composite materials, it can be seen that the majority of methods require the composite structure be either taken to a test house or that relatively complex and large equipment be taken to the structure site. In each case the equipment is large, requires a high level of competence and is typically expensive.

Arguably the range of defects is wide and so requires advanced techniques to detect their presence, which is described in Section 2.1; further research is required to comprehensively analyse each potential defect as to the severity or risk they impose on the structural integrity of composite material. It is understandable that health monitoring advances have not been kept in line with current advances in materials and their applications. Research will continue in this area and progress to what composite defects should be monitored to adequately evaluate the structures' health before investigating new approaches to resolve the current lack of technology.

Disclosure statement

No potential conflict of interest was reported by the authors.

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