A Review on Inspection and Maintenance of FRP Structures

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Abstract. FRP is extensively used today in all domains like concrete structures in Civil engineering, spacecraft in Aerospace Industry. It is also used in elevator and bridge cables. Although FRP has some remarkable properties, it undergoes fatigue and damage and sometimes, undetectable defects are formed. Defects like de-lamination or voids occur due to manufacturing errors, or exposure to external environmental factors can result in BVID. Thus, FRP structures have to undergo inspection to ensure its continued use and safety. The inspection and maintenance methods most commonly employed in FRP structures are NDT or Non-Destructive Testing and CM or Condition Monitoring. The integral part of both, NDT and CM is SHM. NDT is a type of inspection method wherein the sample is tested without damaging it whatsoever. NDT is commonly used for reasons such as low cost, high reliability. The techniques involving NDT are Acoustic Emission Testing, Thermography, Ultrasonic Testing, Eddy-Current testing, Radiography. This paper discusses and reviews the various types of Inspection Techniques in NDT and SHM.

1. Introduction and Application of FRP
FRPs have been extensively used since 1500 BC by the early Egyptians and Mesopotamians and through the variation of properties of FRP, newer products and markets have emerged [1]. The most commonly used FRPs today are GFRP (Glass Fibre), CFRP (Carbon Fibre) and AFRP (Aramid). The domain of application of these fibres is based solely on the properties exhibited by them. In the Construction Industry, FRPs are used widely as reinforcements for concrete structures primarily due to reasons such as high strength, chemical durability, and high corrosion resistance. Carbon Fibres and Aramids are most commonly used as reinforcements [2]. FRPs are also used significantly in the Aerospace Industry in aircraft fuselage and control surfaces and especially as Heat Shields in rockets where CFRP is often used for its high heat resistance [3]. They can also be used in bridge cables and elevator lines for its high strength to weight ratio, good tensile characteristics [4].

2. Defects in FRP and their cause

2.1 BVID
Although FRP exhibits various unique properties in different forms, they are all susceptible to damage and fatigue over time and defects such as BVID or Barely Visible Impact Damage can occur in the structures especially in CFRP [5]. BVID is formed due to Low Velocity Impact which causes delamination internally in the structure and may not be noticeable. These delamination regions grow over time resulting in decrease in stiffness, strength and eventually failure [6]. Failure in a material can either occur during service conditions [7] of the structure or debris impact during runway operations [5] or due to manufacturing errors such as dropped tools [5]. Failure is independent of the fibre properties
and crack propagation occurs between the matrix and the fibre due to tension, shear or compressive loading.

2.2 Environmental Factors

Failure due to fatigue occurs due to long time exposure to external environmental conditions such as sunlight, moisture etc. In Paul Böer, Lisa Holliday, Thomas H.-K. Kang [8], CFRP was tested for shear and was immersed in water at different temperatures and significant deterioration was observed upon increasing moisture and temperature and further increase in temperature resulted in greater deterioration. Similarly, in Paul Böer, Lisa Holliday, Thomas H.-K. Kang [8], two different CFRP sheets, one surfaced with a protective coating and the other by epoxy matrix were exposed to sunlight over a duration of 10 years, placed at different sites namely Japan and Canada. The first type of specimen gathered an uneven surface but no internal damage and the second specimen underwent drastic colour change from blue to yellow due to degradation of resin matrix which lowered the bending strength. Exposure to sunlight weakened the intra-ply region between the fibre and matrix. This has been illustrated in Figure 1.

Constant inspection, testing and maintenance are very much required in all fields to ensure safe use and service of the structure. Quality testing and regular inspection is the norm to ensure safer and guaranteed functioning of the structures for its stakeholders. The main issue faced is Destructive testing which results in large costs in specimen and test setup. To compensate for the above disadvantage, NDT (Non-Destructive Testing) is used which will be explained in the next section.

3. Introduction to NDT and CM, SHM

Non-Destructive Testing is the testing and inspection of various specimens, materials wherein the material does undergo any damage whatsoever. NDE emphasizes on a range of techniques such as Ultrasonic Testing, Thermography, etc. Almost everything from spacecraft to elevator cables to power stations are inspected using NDT [9]. The overall maintenance of a structure consists of NDT, CM (Condition Monitoring) and SHM (Structural Health Monitoring). NDT is employed during the manufacturing phase of a structure wherein potential flaws can be corrected whereas CM is an ongoing assessment wherein the structure is tested during its operation. SHM is the main objective of maintenance which gathers the results from NDT and CM for the overall maintenance [10].

Relation between NDT, CM and SHM have been shown illustratively in Figure 2. NDT has replaced Destructive Testing for its cost, reliability and safety [11].

4. NDT, CM AND SHM Techniques

4.1 Pulsed Eddy Current Measurement

In Yunze He, Gui Yun Tian, Mengchun Pan, Dixiang Chen, [12], PEC or Pulsed Eddy Current has a greater scope and advantage over simple Eddy Current Methods. The specimen used is a Sandwiched Honeycomb Structure. The fibre used is CFRP for its high heat resistance and strength to weight ratio. It is also known for its electromagnetic induction properties hence

![Figure 1. Graph plot of percentage strength and exposure time for FRP](image1.png)  
![Figure 2. Relation between NDT, CM and SHM](image2.png)
they can be tested by this method [13]. The Eddy Current setup consists of a coil excited by an AC source which is brought towards a sample and hence Eddy Current is induced through Electromagnetic Coupling. The magnetic field created in the sample induces a secondary field in the coil. [14] The defects present change the Eddy Current circulation around the sample and hence changes in magnetic field can be recorded by introducing a secondary coil [13] and thus change in frequency signals are measured from which defects are detected. Figure 3 illustrates different waveforms of different ECT techniques.

4.1 Advantages, Disadvantages and Inspection Factors

The process is less hazardous, simple, reliable in Surface and Subsurface damage detection, and is economical [12] and in PEC, time required is less [14]. But EDT is very time consuming and cannot be applied to non-conducting materials [15]. Damages such as matrix cracking is undetectable [13]. Factors for detecting defects are defect properties, electrical conductivity of the material. Highly sensitive Magnetic sensors and user-friendly systems can reduce human efforts and time [14].

4.2 Acoustic Emission Testing

In Acoustic Emission Testing, defects can be detected through acoustic emissions generated by a sample on loading. A sample is deformed by loading it and strain energy per unit volume is emitted in the form of elastic waves [16], sensors located on the surface of the sample record transient waves due to deformation [17] such as fibre break, plastic deformation, and crack propagation [18].

Some of the applications of AET are detection of Creep in High Energy Piping (HEP) systems and pressure vessel inspection [19]. Compared to the other general techniques used in NDT, Acoustic Emission Test differs by 2 ways [18], one the signals detected are emitted by the specimen, not by external sources, hence AE test is performed on structures during operation when defect propagation occurs [20], this has been illustrated in Figure 4. Second, strain is measured here, whereas geometrical defects are measured generally in NDT.

4.2.1 Advantages, Disadvantages and Inspection factors

Various types of defects, failure mode [18] can be detected by several emission signals and simple equipment is used here [15]. This process involving volumetric inspection is fast [20]. However, distinguishing the various acoustic emission signals produced that overlap one another is a challenge [21]. Only localized results such as local stress can be detected [15]. The Automation process is complex as it involves linking the transducers and the sample with a special type of fluid [15]. If loading on the structure is not high enough to produce Elastic waves, flaws can sometimes go undetected [20]. Another drawback is high sound generation that affects the signals measured [20].

![Figure 3](image1.png)

**Figure 3.** Illustration of excitation waveforms for different ECT techniques

![Figure 4](image2.png)

**Figure 4.** Cumulative AE counts as function of the applied stress
4.3 Thermography
Thermography is the mapping of isotherms over a structure [22] or is the thermal imaging of a structure. In Thermography, defects caused within a structure brings changes in the heat flow which changes the surface temperature at local points [22] and radiation produced is detected by IR cameras.

Detecting flaws using this technique usually depends on detection of thermal gradients in the structure, emissivity of the structure to produce radiation [23]. Thermography is classified as Passive and Active Thermography and both classifications involve use of IR cameras.

In Passive Thermography, the IR camera is placed in front of the sample and a thermal map is generated and in Active Thermography, the surface of the sample is first heated by an external source and the IR camera then records the temperature decay rate as penetration of heat occurs. Defects in the structure show variation in decay rate and surface temperature distribution [22]. Depending upon the decay rate and heat penetration, Active Thermography can be classified as Modulated Thermography (MT), Pulse Thermography (PT) and Pulse Phase Thermography (PPT) [24].

4.3.1 Advantages, Disadvantages and Inspection Factors  IRT can scan large surface areas in less time with a single shot [25] and both outer and inner defects can be obtained [15]. The process is simple and a non-contact one [26] and the price of IR cameras used is reasonable today [22]. But, the sensitiveness of inspection is a challenge as some materials have emissivity that results in either rapid heat production or sometimes, undetected defects [13].

4.4 Ultrasonic testing
In Ultrasonic Testing, high frequency soundwaves are propagated towards a sample possessing some acoustic impedance and defects present in the sample reflect the soundwaves back. These sound waves are then displayed on a screen. High frequency waves are used to obtain defects precisely and low frequency soundwaves are used to detect internal defects [27]. The UT setup consists of a receiver which generates high voltage electrical signals [28], an ultrasonic transducer or a probe which converts electrical impulses into sound waves. These sound waves are then propagated towards the sample and defects in the sample reflect the sound waves back to the source which can be visualized on a CRT screen.

4.4.1 Advantages and Disadvantages  Results obtained in this method are accurate [15]. Penetration depth for flaw detection is high and equipment used provides instantaneous results [28]. But the entire structure cannot be analysed and experimental setup is costly [15]. Materials with irregular shape, rough surface cannot be tested and a special fluid is required for sound wave propagation [28].

4.5 Radiography
In Radiographic Testing, a sample is subjected to a certain penetrating radiation depending on the nature of the material and a recording medium such as screen projects the defect. For less dense materials such as Aluminium, X ray Radiation is projected and for denser materials, Gamma rays are projected [27]. The recording medium or screen is placed behind the sample. The dark areas on the medium represent defects and the light ones represent no defects or areas of low radiation [27].

4.5.1 Advantages and Disadvantages  The method of testing is extremely accurate, sensitive, is a non-contact process and most defects such as porosity can be detected. The method eliminates safety hazards [27]. However, high energy supply for experiment conduction is a challenge [27].

5. Conclusion
The various techniques used in NDT are reviewed. All techniques have equal importance in the field of Inspection and Maintenance. Although some techniques such as Thermography stand out in quality of inspection, others too have their pros and cons and requirements which we have to suitably choose from in order to maximize the quality, quantity and improvement of these techniques. Although some techniques were selectively invented for specific testing of FRP, other techniques were invented to reduce human efforts and provide us with the basics of damage detection. The issue of expenses will
always be a major issue in any field and therefore, all these factors especially the application of these techniques should be chosen suitably in order to better the field of inspection and maintenance in FRP.

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