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General Strategy to Implement Sensing Capabilities in GFRP Components

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ABSTRACT: In modern time, Glass Fiber Reinforced Plastic (GFRP) components have been developed with sensing ability to monitor various engineering applications. Some of these components have self-diagnostic and self-repairing abilities. It is difficult to incorporate self-healing abilities in GFRP components. However, sensing abilities are integrated using the easily blendable sensors such as carbon fibers, optical fibers, metal inserts etc. The sensor integration in the GFRP composites should be synergistic one. The GFRP components serving in different applications are suffering from various kinds of material degradation. In this regard, intelligent structural components are developed to monitor the defects at all the stages from its crawl to the grave.

This paper presents the studies related to the integration of the sensing strategies in GFRP components. Strain gauges, carbon and optical fibres are used for implementing the sensing in GFRP materials. GFRP Components such as leaf springs and composite pipes are fabricated and tested to study their sensing behavior and SHM implications. Based on the study, a general procedure is developed to implement the sensing strategy in the GFRP components. The damage modelling and sensor deployments are the two main stages of this strategy. Sensor wiring or connections are carefully made based on signal (electrical/optical) type.

KEYWORDS: GFRP, sensing, damage modeling, sensor deployment.

I. INTRODUCTION

The Fibre Reinforced Plastic (FRP) is a class of synthetic material consisting of polymer resin reinforced with glass fibres. High strength to weight ratio of the FRP composite motivated its use in aerospace structures, automobiles, and civil engineering structures. Apart from these merits, matrix cracking, delamination and degradation are the most common failures in FRP composites. These failures occur due to faulty manufacturing methods or surrounding conditions of the FRP structures. Failures may cause severe damage to the entire structure without giving any warning to the occupants. This may raise the questions regarding the fitness of FRP material, thus limiting its area of application.

Identification of failure in FRP structures before it affects the most is the important task. Visual inspection is one of the oldest yet cheapest methods used for structural monitoring. But huge or/and remote structures cannot be monitored using this method. The continued efforts of the many researchers have resulted in high-performance FRP composites with built-in sensing and actuation capabilities. This multi-disciplinary field of research has encouraged the development of structural health monitoring (SHM) system for FRP structures.

The performance of any SHM system depends on the efficient implementation of the damage detection strategy in the structure. This involves the operational evaluation, data acquisition, information processing and development of failure model. The operational evaluation consists of damage definition, loading and environmental

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conditions of the structure. Data acquisition involves the selection of type and number of sensors and its location. It also consists of data transmission and storage hardware.

II. IMPLEMENTATION OF SENSING CAPABILITIES

FRP structures have many implementation issues like repair, ageing and anisotropic behaviour etc.[3]. These adverse properties need to monitor carefully to predict and prevent unanticipated failures of FRP structures. Delamination, matrix cracking, stress concentration areas in FRP structures are more prone to failures [3]. Identification and monitoring of these regions of FRP structures are key issues to be considered to ensure structural integrity. In this regard, Structural Health Monitoring (SHM) techniques of FRP structures are taking new hypes [4&5]. Advanced sensors, efficient signal processing units and intelligent controllers are contributing a lot to the development of more reliable SHM systems. Its reliability depends mostly on sensing capabilities of GFRP composites. Implementation of sensors in FRP structure is a very important aspect.

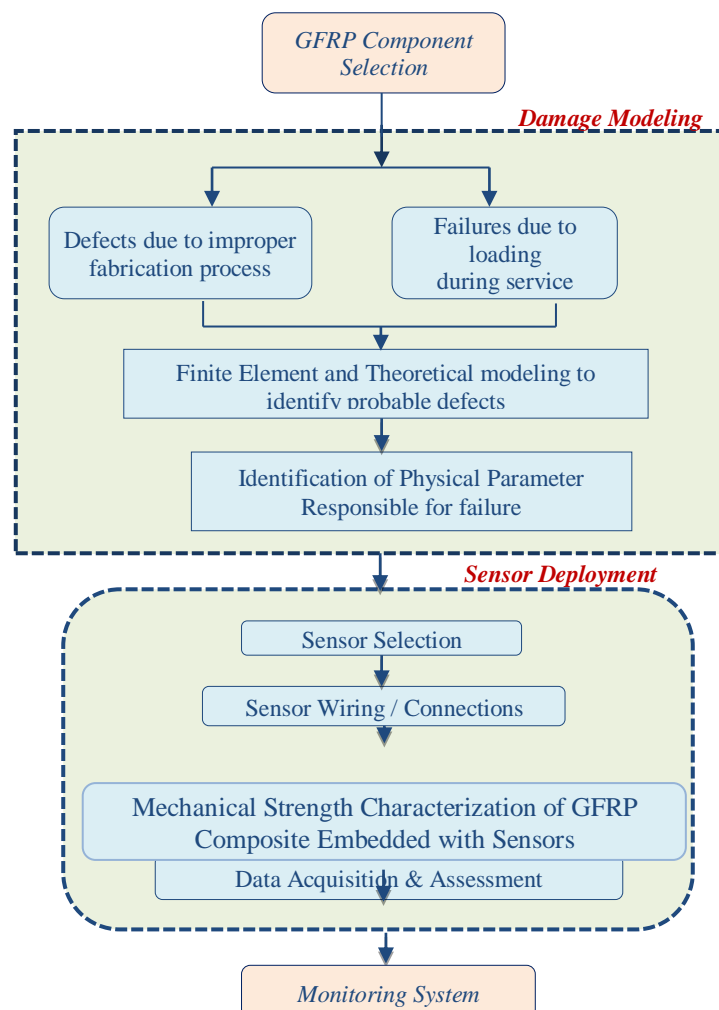


Fig.1 Sensor Deployment Strategy for GFRP Components

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In this regard, an attempt is made to develop the sensor deployment strategy for the GFRP components and structures. Based on the experimental and literature review a sensor deployment strategy for GFRP components is developed as shown in Fig.1. The damage modeling and sensor deployments are the two main stages of this strategy. Sensor wiring or connections are carefully made based on signal (electrical/optical) type.

2.1 Damage Modeling

Damage modeling of GFRP composite is associated with numerous factors that make it complex for failure prediction. Major failure causing factors are improper fabrication processes, in-service stresses due to loading and the harsh environmental condition surrounding the component [7&8].

The improper fabrication process of GFRP composites has more likely to develop defects. Uncontrolled curing is one such defect causing aspect. It develops voids or porosity in the matrix and induces residual and shrinkage stresses. The inclusion of foreign particles in the matrix during fabrication leads to defects in GFRP components. These components are cured in the oven or naturally cured at room temperature. Polymerization shrinkage stresses are induced due to the non-uniform curing process. This leads to increase in voids contents, warpage and creation of microcracking in the components. The polymerization shrinkage increases with resin percentage and depth of the GFRP components. Shrinkage is almost 10-40 μm for the first few minutes of the curing and it increases up to few millimetres over an entire period of curing [11]. Shrinkage and residual stresses can be predicted by using cure kinematics and viscoelastic modeling of GFRP components. For epoxy resins, the autocatalytic model is used to understand the cure kinematics [12]. Based on the theoretical and FEA studies damages and failure characteristics in GFRP components can be understood. This helps to prepare sensor deployment strategies for curing.

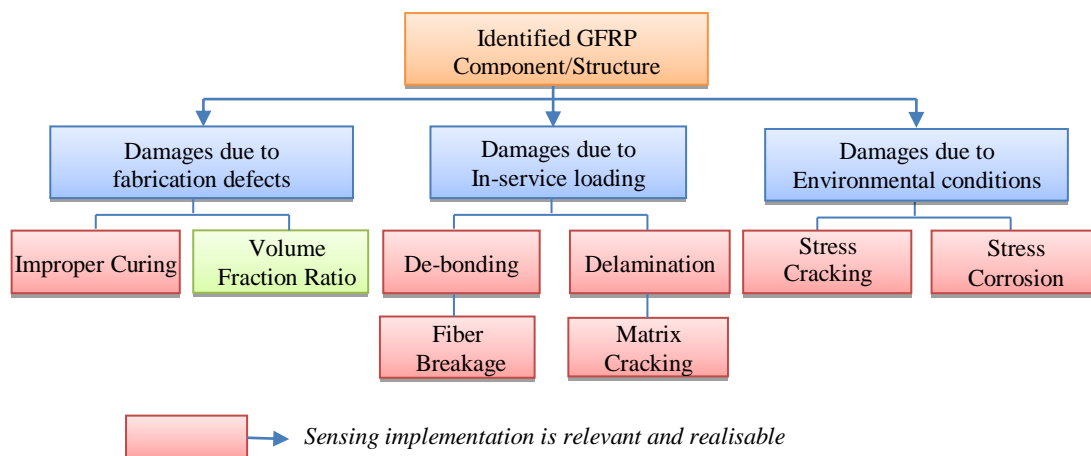


Fig.2 Monitoring of Defects in GFRP Components

GFRP composites are degraded due to in-service static, dynamic and fatigue stresses [65]. These stresses lead to several failure mechanisms that originate defects in the materials. Among these, few results into the catastrophic failure of the entire structure. Fibre breakage, delamination, matrix cracking and debonding are such major defects initiated due to overloading stresses. Environmental factors such as temperature, humidity and chemical nature of atmosphere can degrade the strength of the GFRP composites. Most of the time, this degradation is referred as stress corrosion and it occurs at the surface of the composites [10]. The stress cracking is also a possibility in GFRP composites due to environmental factors [9]. Fig 2 illustrates the possible defects in the GFRP components during fabrication and in service. The red blocks in the figure indicate the defects that can be predicted by monitoring parameter initiating the defects. Important defects causing parameters are induced strains due to in-service loading and temperatures variation around the structure.

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Tsai-Wu [18], Tsai-Hill [16], Azzi-Tsai [17], Hoffman and Chamis [19] criteria are frequently used in industries to understand the FRP composite failure mechanisms [15]. These criteria are based on material type, component geometry and loading. Puck's action plan based failure criterion is used for better understanding of FRP material failure physics [20]. Recently, an international initiative is known as World Wide Failure Exercise (WWFE-III) [25] is formed to predict the failures in FRP composite materials [21]. The defects in the GFRP components are identified using this failure exercise accurately. Most of the commercially available finite element (FE) tools are incorporated the WWFE accepted failure models.

Fiber-matrix debonding is associated with the properties of fiber, matrix and their interfacial bonding. The debonding in GFRP composites reduces the natural frequency, alters the vibration modes and degrades the overall performance of the structure considerably [13]. The researchers [22] show that finite element models are efficiently used for analysing the fiber-matrix interface debonding effect. These FE tools use Carrere, Laurin and Maire's model [22] for predicting the damages.

Fiber breakage in composites is due to tensile loading of a structure. Many analytical models based on linear elastic fracture mechanics have been developed. Among these, the finite stress distribution model, the inherent flaw criterion, the damage zone model, and the progressive failure model are important in understanding the fiber breakage criteria [14]. Recently, WWFE accepted Chamis' model [19] is used by many industries for fiber breakage prediction in GFRP components.

Matrix cracking is also termed matrix microcracks, intralaminar cracks, ply cracks, and transverse cracks [27]. Matrix cracking occurs due to tensile stress, fatigue stresses, temperature variation and thermocycling [26] in FRP composites. More often this defect leads to delamination of composites laminates. Chamis' model [19], Soutis-Kashtalyan's model [23], McCartney's model, Pinho's model, Talreja's model, Varna's model are important in matrix cracking prediction. These models guide sensor deployment strategy in the GFRP components for monitoring the damages.

Failure due to delamination is observed in the laminated GFRP composites. The main cause of the delamination is due to the insufficient reinforcement along the thickness of the GFRP component. Matrix cracking is a major reason for delamination in FRPs. In general, delamination is produced by interlaminar stresses due to incompatible material properties, discontinuities in the structure and uneven deformation [21]. Many delamination models are used to assess the place and degree of severity of delamination due to in-service stresses. However, Soutis-Kashtalyan's model [23], Ladeveze's model [24] and Chamis' model [19] are frequently used to analyze damage parameters responsible for delamination in FRP composites.

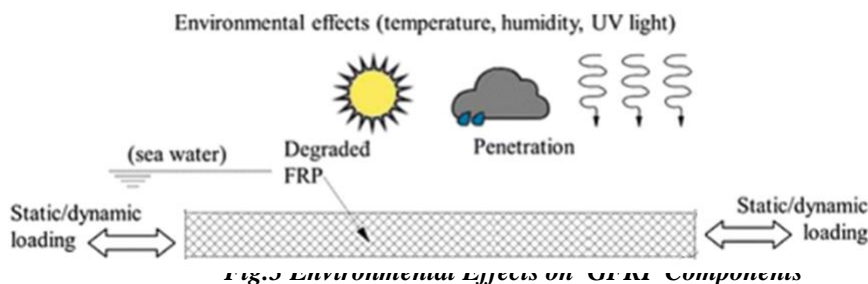


FIG.3 ENVIRONMENTAL EFFECTS ON GFRP COMPONENTS

Fig 3 shows various factors such as temperature, humidity, UV light and chemical nature (alkaline and acidic) of the atmosphere are responsible for GFRP material degradation [37]. Initially, composites experience stress corrosion due to environmental factors and at later stages, it progresses into stress cracking, debonding and delamination. The FRP strength degradation is analysed by using "Stress Corrosion" Models [28]. The mathematical models discussed in this section are used for analysing the failure behaviour of the GFRP components. This helps in implementation of sensing strategy for different components having various geometrical shapes, in-service loading and environmental conditions.

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2.2 Sensor Selection

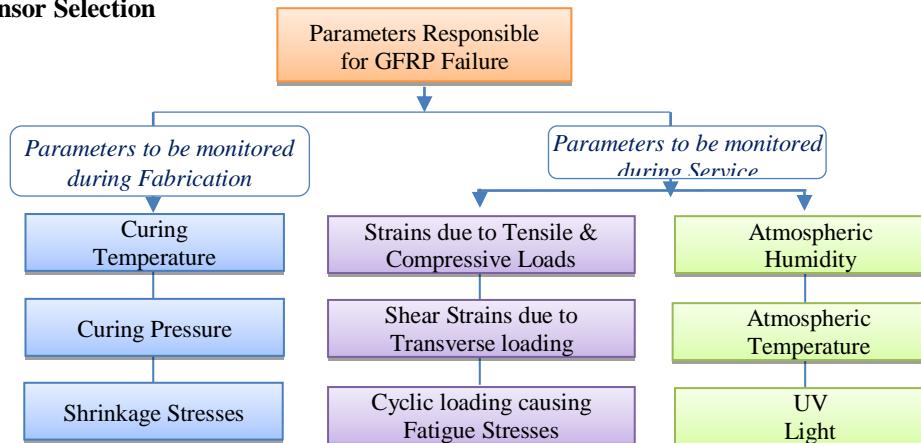


Fig.4 Critical Parameter Identified in GFRP Components for Monitoring

The parameters responsible for fiber breakage, matrix cracking, debonding delamination etc are analysed using mathematical models. The stress concentration areas, the tendency of critical parameters and physical phenomena responsible for failure are identified in the damage modeling. This guides in developing the sensor deployment strategy for GFRP components. The GFRP components are used for diversified engineering applications. In all these applications, failure originating factors depends on the geometry, usage, fabrication process, environmental and in-services loading. Such common and critical damage causing parameters are listed in Fig 4.

Monitoring of curing parameters like temperature, pressure and shrinkage stresses helps to fabricate the sound GFRP components. By controlling these parameters components without any voids, wrinkle, resin rich or resin starved areas can be fabricated. Researchers [36] have developed many inline sensing methods for monitoring the production of FRP components based on optical fiber, electrical or sound wave techniques. Carbon fibers are used for monitoring the curing by measuring the changes in electrical capacitance and resistance in the composites during fabrication [29&31] of GFRP components. Fig. 5 shows the carbon fiber blended GFRP composite cure monitoring strategy formulated by [29]. Recently, for monitoring the complete cure kinematics of composites FBG optical sensors [30&35] are used. The sensing system used in the curing process can be used for in-service health monitoring [36] with appropriate recalibration.

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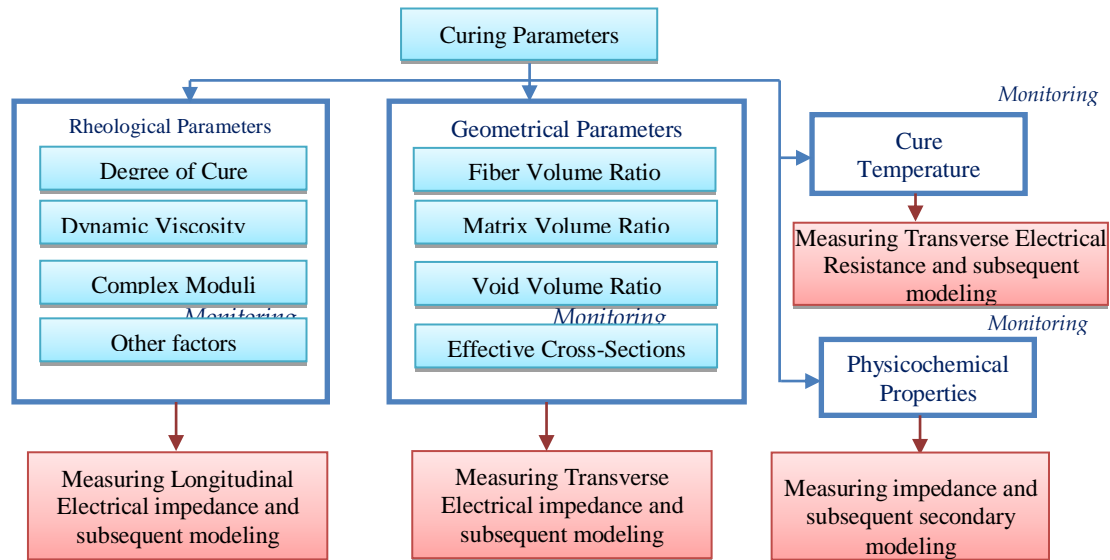


Fig.5 Cure Monitoring Strategy Using Carbon Fiber Blended GFRPs

Carbon Nano Fibres (CNF) and Multiwall Carbon Nanotubes (MWCNT) are blended in GFRPs for monitoring humidity [31] levels in the GFRP structures. The CNF and MWCNT particles change the electrical resistivity of GFRPs, when the humidity level in the composite material varies [33]. Sometimes the humidity sensor is integrated for online conditional monitoring of GFRP composites. This sensing system has a limitation of monitoring the humidity at the localized areas of the structure [32]. Fiber optic techniques mostly preferred for monitoring the humidity in GFRP composites [33]. Most of these optical sensors use water vapour condensation principle [34] for humidity measurement. Recently, organo-silica (high humidity sensitive material) coated FBG optical sensors are used for measuring the relative humidity (RH) [35] for SHM of structures. These FBGs can give precise sensing over a long period of time without degrading its properties.

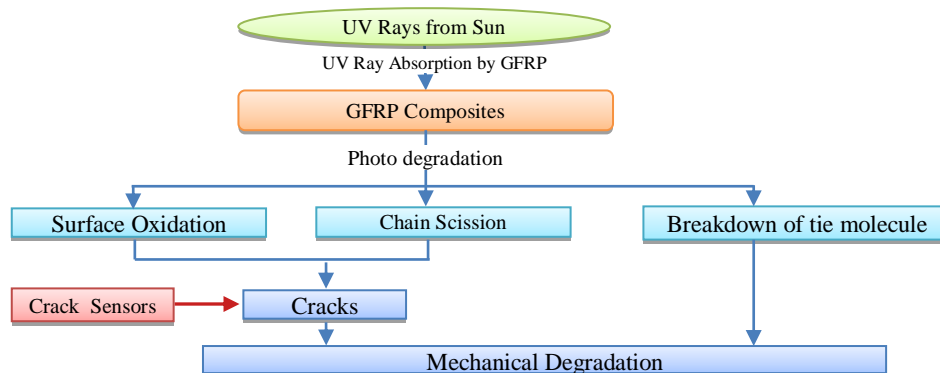


Fig 6 Effect of Ultra Violet Light on GFRP Composites and Monitoring

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Photodegradation of GFRP composites take place due to ultraviolet (UV) ray absorption [38]. This results in surface oxidation, chain scission [39] and breakdown of molecules of polymers. The surface cracks are formed due to UV ray absorption. These cracks progress into bigger and lead to failure of entire structures. The effect of UV light on GFRP composite is depicted in Fig.6. By deploying optical sensors such as Fiber Loop Ring Down (FLRD) crack sensors in the GFRP composites the microcracks generated from the UV light effect can be monitored [46].

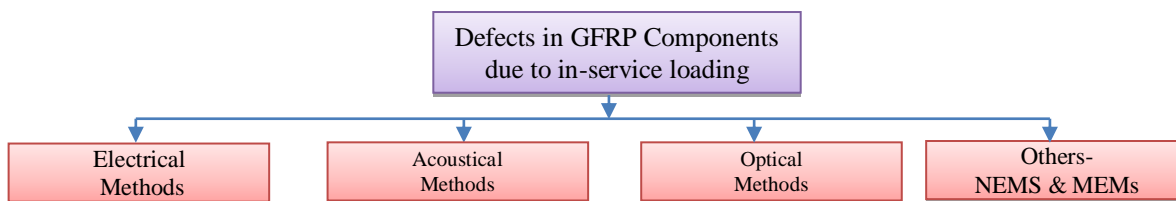


Fig.7 Sensing Technologies Used for Monitoring Defects

Apart from the environmental factors, major degradation takes place in GFRP composites due to in-service loading. GFRP components are subjected to tensile, compression, shear, fatigue and thermal stresses during service. These stresses initiate the defects such as fiber breakage, matrix cracking, debonding, delamination etc. By detecting the induced stresses at early stages can avoid the catastrophic failure of the entire GFRP structure. Failure mechanisms help in selection of appropriate sensors and developing a deployment strategy for SHM system. Fig.7 shows the different embedded sensing technologies used for detecting the induced defects in the GFRP composites. Electrical and optical methods are two basic forms of online sensing techniques used for measuring the internal strains in the GFRP composites. Acoustic methods are used to measure cracks, voids and fiber breakage in the composites. This method requires bulkier instrumentation that makes difficult to monitor remote structures like aircraft wings and other aerospace structures. Studies [47] show that strain gauges, carbon fiber sensors, PZT sensors, optical fiber sensors, MEMs and NEMS sensors are generally employed for sensing the in-service defects in a GFRP structure.

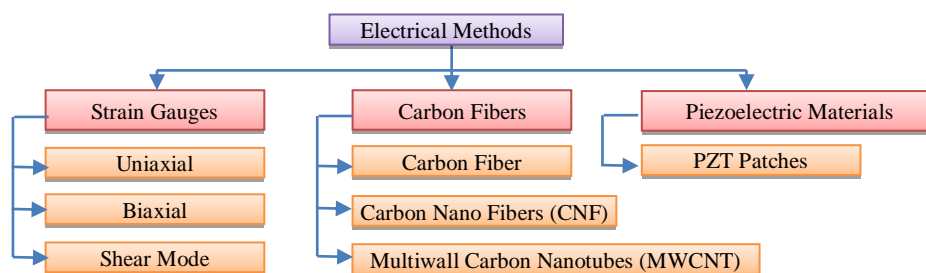


Fig.8 Electrical Sensors used for Monitoring Induced Strains

Fig. 8 shows the various means of strain monitoring systems employing electrical methods. The axial and circumferential strains are measured using the multiple sets of strain gauges and results are verified by comparing with theoretical values [40]. Strain gauges are suitable for measuring strains in the small size polymer components subjected to tensile, compression and shear loading. Sometimes, capacitive sensors cells are constructed using stretchable polymers and metal plates for measuring the induced strains [1]. In recent days, embedded Carbon fibers(CF) are used as sensors due to the excellent electrical properties that enable them to construct it as resistive or capacitive or impedance-based sensor. Researchers [43] blended carbon fibers in GFRP composites and found that induced strain results in a change in electrical properties. The monitoring of resistance and capacitance variations helps in detecting

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fiber breakage, matrix cracking voids etc[40&41]. Studies [42] also suggest that DC voltages are appropriate for detecting fiber breakage while AC voltages are used for monitoring matrix cracks in the FRP composites.

The electrical sensing system is integrated into GFRP composite leaf spring and composite pipes. Strain gauge and carbon fiber sensing systems are integrated into GFRP leaf spring and pipes and performances are evaluated. The study suggests that the electrical means of sensing is one of the easily realizable and reliable sensing methods.

Piezoelectric (PZT) fibers are embedded in FRP composite to implement and sensing and actuation [43] capabilities. Piezoelectric lead-zirconate-titanate (PZT) fibers aligned in glass fiber directions are used for detecting the leakage in the pipeline by employing Acoustic Emission(AE) methods[44]. PZT wafer is another form piezoelectric sensors having stable and repeatable characteristics [45]. An array of miniature surface-mounted piezoelectric wafers (PZTWAS) is used for impact damage detection in GFRP composites [46]. Generally, these PZT wafers are used in aerospace applications for impacts are used for monitoring the vibration and load intensity in the FRP structures [48].

Optical Fiber Sensors (OFS) are most accurate in-service defect monitoring systems used in aircraft structures made of FRP composites. Static and detection [35]. In another way, electrical characteristics of PZT material is utilized in PZT patch sensors. These sensors dynamic strain due to impact loading is monitored using the network of embedded Fiber Bragg Grating (FBG) sensors [49]. The OFS embedment in the GFRP composites will not sacrifice the mechanical integrity of the structure. Along with the standard FBG sensors, microstructured fibers (MOF), Fabry-Perot (FP) Interferometry FOS, Polarimetric Sensors, Micro bend OFS, distributed sensors and hybrid sensors are some of the commonly used FOS technologies.

Table 1 Types of OFS and their Applications [2&6]

OFS type	Type of Sensing	Applications
<i>Fiber Bragg Grating(FBG)</i>	<i>Quasi distributed</i>	<i>Strain, Displacement, Temperature</i>
<i>Micro-structured Fibers(MOF)</i>	<i>Distributed</i>	<i>Strain</i>
<i>Fabry-Perot(FP) Interferometry</i>	<i>Point</i>	<i>Temperature, Pressure</i>
<i>Polarimetry OFS</i>	<i>Distributed</i>	<i>Strain, Temperature</i>
<i>Micro bend OFS</i>	<i>Distributed</i>	<i>Strain, Temperature, Humidity</i>

Table 1 shows the commercially used OFS and their applications. MOF optical sensors have an ability to monitor the transverse and axial strains at the same time [51]. Composite curing and residual strains are monitored using MOF sensors. Micro bend FOS is used for online temperature, pressure and defect (delamination) monitoring [52&53]. Fabry-Perot Interferometers are cost-effective OFS used for monitoring environmental parameters in addition to strain, temperature, vibration etc. [50&54] Buffer coated polarimetric OFS are most suitable for accurate strain and temperature measurements [55]. In distributed OFS single fiber is used for measuring many parameters like strain, temperature, delamination etc. [56]. Hybrid OFS are employed two or more fibers for measuring the strain/temperature precisely. Recently, polymer FBG sensors are used instead of silica FBG sensors. This polymer OFS are more sensitive to humidity and temperature [120].

OFS is easy to integrate into GFRP composite and their integration will not degrade the mechanical properties of OFS as well as the GFRP structure. However, the data acquisition and assessment system are costlier. This limits OFS usage in the smaller structure. In this regard, a cost-effective Content-Based Image Retrieval (CBIR) System is developed for optical fibers for sensing temperature in the GFRP composite. Studies suggest that this system can be easily integrated and used for SHM.

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2.3. Data Acquisition and Data Assessment

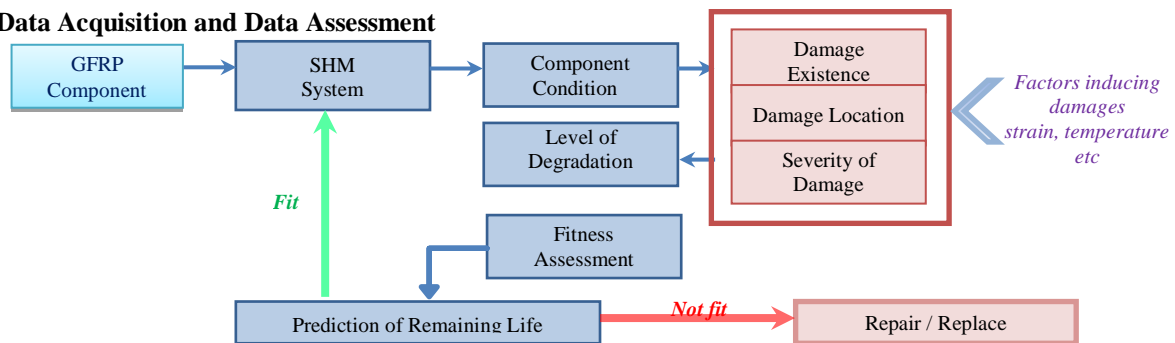


Fig.9 Data Acquisition and Data Assessment for GFRP components

After completing damage modeling, sensor selection and deployment in the GFRP components, the continuous data acquisition and assessment is carried out to monitor the structural integrity. Fig 9 shows the typical flow chart showing the data acquisition and assessment system for GFRP components. This involves a lot of transmission line connected to the sensors and data handling systems. This system continuously processes the sensor information to assess the component condition and caution the occupants or attendants about the possible hazards due to GFRP component damage. Further integration of expert system and artificial intelligence in the SHM system may enhance the accuracy of failure prediction.

III. CONCLUSIONS

The factors causing damages in GFRP composites and corresponding sensor selection are presented. Based on the study, the typical sensor deployment strategy for GFRP component is developed to help the further studies. Data acquisition and assessment flowchart is proposed for developing the Structural Health Monitoring (SHM) system for GFRP components.

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