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Review on Strain Monitoring of Aircraft Using Optical Fibre Sensor

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***Abstract*—Structural health monitoring of aircraft assures safety, integrity and reduces cost-related concerns by reducing the number of times maintenance is required. Under aerodynamic loading, aircraft is subjected to strain, in turn causing damage and breakdown. This paper presents a review of experimental works, which focuses on monitoring strain of various parts of aircraft using optical fibre sensors. In addition, this paper presents a discussion and review on different types of optical fibre sensors used for structural health monitoring (SHM) of aircraft. However, the focus of this paper is on fibre bragg gratings (FBGs) for strain monitoring. Here, FBGs are discussed in detail because they have proved to be most viable and assuring technology in this field. In most cases of strain monitoring, load conditioning and management employs finite element method (FEM). However, more effort is still required in finding the accurate positions in real time where the sensors can be placed in the structure and responds under complex deformation.**

***Keywords*—technology; electronics; optoelectronics; photonics; telecommunications; signals; circuits; systems; applications**

I. Introduction

ENGINEERING structures are intended to be safe such that there is no catastrophic failure. Maintenance of these structures should have a lightweight design, minimum occurrence of maintenance without negotiating its safety, sustainability and reliability. Wireless communication, sensing technology, high power micro processing, and many other technologies are implemented to identify parameters such as strain, temperature, light, sound, vibration, rusting, electromagnetic interference (EMI). A modern era in structural design and its maintenance has emerged and is called as structural health monitoring (SHM) [1].

SHM can be broadly defined as implementing a detection strategy to allow the loading and damaging of structures like civil, mechanical, aerospace engineering infrastructure by recording, analyzing, localizing, and predicting such that non-destructive testing becomes an indispensable part of the structure [1][2]. Structures such as buildings, dams, pipelines, aircraft, ships, nuclear reactors, bridges, and others require design structures that are safe for public use, meet the standards, and has to ensure society's economic and industrial prosperity [3][4].

The majority of the constructions such as high rise buildings, large scale sports avenues, tunnels, and offshore platforms face damages due to environmental pollution aspects of physical, chemical, and corrosion processes forming deterioration of concrete structures [5][6].

Concrete dams promote prosperity by providing water for irrigation, hydroelectricity generation, and flood control. Their performance suffers due to age-related, creep, temperature, water level, shrinkage, earthquake, etc. Structural health monitoring for dams is termed as dam surveillance, predicting its long-term behavior by forecasting appropriate thresholds [7][8].

In critical structures such as bridges, replacement is impractical and maintenance and/or repair are expensive. Structural hazards, damages such as cracks on a conventional bridge are unacceptable and incurs additional maintenance cost. Increased demand of transportation may lead to the higher risk associated with their unexpected failures, resulting in risking the passenger safety and increase in full lifecycle cost. Innovative SHM methods that can continuously monitor and yield more efficient maintenance of the railway network are required [9–11]

Pipelines used for energy sources transmission suffer from corrosion, stress, fatigue, cracks, landslides, and damage from thefts leading to leakage and failure with severe economic and environmental consequences. A feasible solution for this involves a damage detection process known as SHM [12][13]. Life-cycle performance of ship structures changes their physical properties, such as reductions in stiffness resulting from cracks, pitting corrosion, and erosion-corrosion due to the interaction of the steel and salted seawater's expensive failure of its structural components. SHM is emerging as a powerful technique in ship structures for collecting accurate information. A network of sensors is used in real-time data generation transmitted and processed in an onboard database [14][15].

SHM techniques and methodologies are successfully used in cultural heritage buildings that were severely damaged by an earthquake and in wind turbines and blades situated in remote or offshore locations, which are often coupled with harsh environmental conditions [16][17].

The number of aircrafts are rising globally as well as their age. This has headed to the increasing demand for aging aircraft. Performance prediction of these aircraft has become a difficult task since they undergo constant upgrades in engines, avionics, and flight control systems [18].

An event that triggered damage monitoring was the Aloha Airlines accident flight 231 in April 1988. The aircraft held cracks due to its increase in age, which resulted in Multisite Damage (MSD), which is the effect of several minute cracks to be more sensitive to cumulative fracture than the sum of all these cracks represented as the length of a single crack. The consequence of this has led to the airworthiness authorities set regulations that the aircraft at the span of 15 years and ahead have to be subjected to enhanced inspection [1].

Valid record-keeping of the damage recognized can prove to be a valuable source of information to distinguish and improve the fatigue crucial areas. The first source of such report is the

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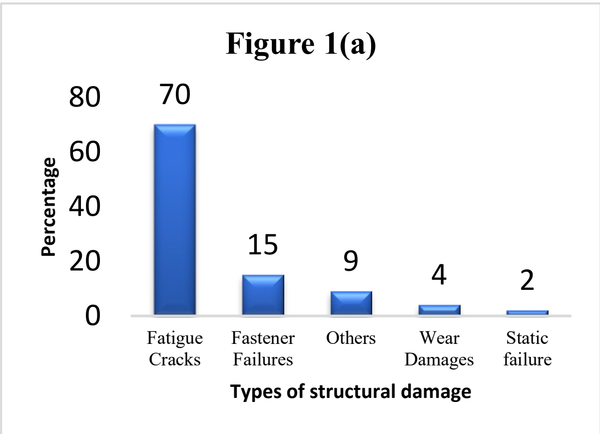
major airframe fatigue test (MAFT), which is performed before the aircraft going into operation, followed by a tear-down analysis after MAFT has been performed. The statistics of such an examination for the Tornado fighter aircraft are given in Fig. 1(a). The damages were reported as fatigue cracks, failures of fasteners, bolts, rivets, wear damages, static failures, and others (e.g., failures of auxiliary structures as load introductions). The fatigue cracks were due to the geometry (change of the stiffness), and holes for joints, bolts, fasteners, and lugs, cut-outs (open holes, etc.) are given in Fig. 1(b).

Similar trends for civil aircraft Boeing 747. It was observed that 714 cracks were identified in a fleet of 61 in Japan during in-service inspection for nearly three years. The fatigue damages were reported as geometry, holes for joints, and others, as shown in Fig. 2(a). Also, after in-service inspection at fuselage, wing, pylon, door, and empennage, fatigue cracking locations are shown in Fig. 2(b) [18].

Piezoelectric transducers are mostly used for passive and active damage detection based on sound and ultrasound. Micro-electro-mechanical systems (MEMS) detect structure damage of few expensive critical structural components and serve periodical enquiring of data [19]. SHM uses wireless sensors for military aircraft, detection of crack damage, corrosion cracking in aircrafts skins, the performance of rotary wing flight systems, and the temperature of next-generation reusable space vehicles. It has been tested on NASA Langley's Airborne Research Integrated Experiments System (ARIES) to validate the wireless communication capabilities, hardware design, software operation, and data acquisition, etc. [19][3].

Optical sensor is suitable for SHM because of its lightweight, no electromagnetic inductiveness, and endurance [20]. One optic can be utilized to multiplex tens or hundreds of optic load sensors, thus significantly reducing the wiring problem [21].

This paper provides a detailed review on strain monitoring using optical fibre sensor used for aircraft. Section II provides information about different types of the optical fibre sensors used for structural health monitoring. Section III explains an optical fibre sensor used for different parameters of SHM in aircrafts. In section IV application of Fibre Bragg Grating in strain monitoring is discussed. Strain monitoring in different parts of aircraft using an optical fibre sensor is discussed in Section V. Finally, a conclusion is provided in Section VI.



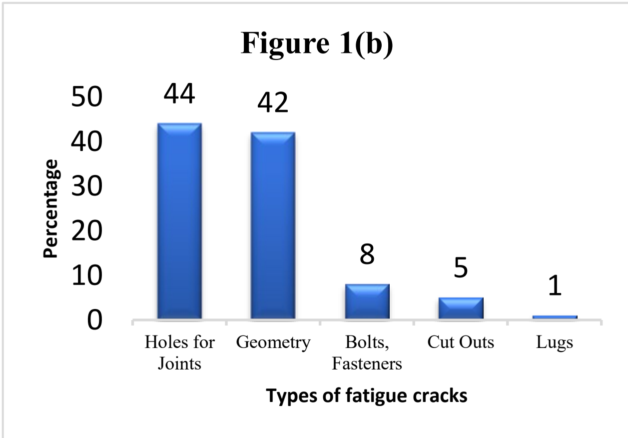
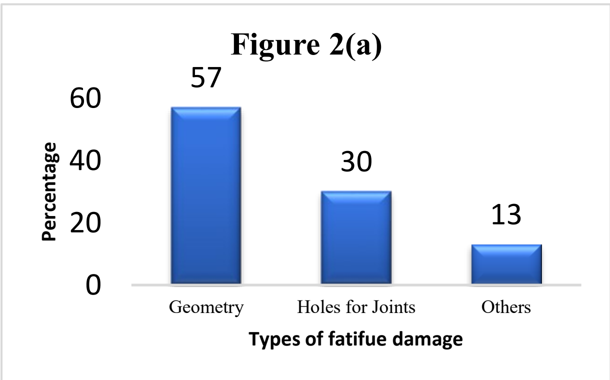


Fig.1. Statistics of damage and fatigue cracks in Tornado fighter aircraft [18]



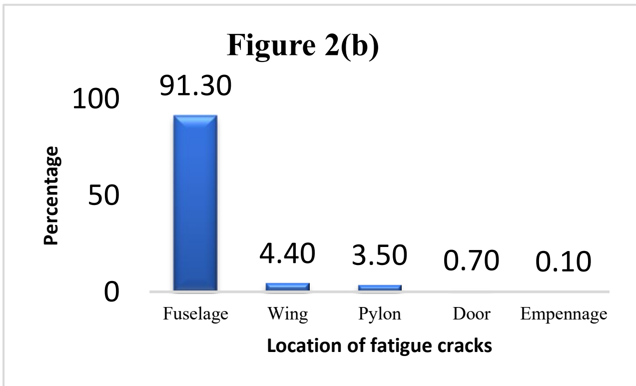


Fig.2. Statistics of damage and fatigue cracks in Boeing 747 civil aircraft [18]

II. Optical sensors for structural health monitoring in aircraft

Optical Fibre sensors (OFS) such as Fibre Bragg grating (FBG), polarimetric, intensiometric and those based on interferometric principles are used since they are insensitive to EM radiation, nonconductive, lightweight, spark free, intrinsically safe, and also their suitability for embedding into structures [22].

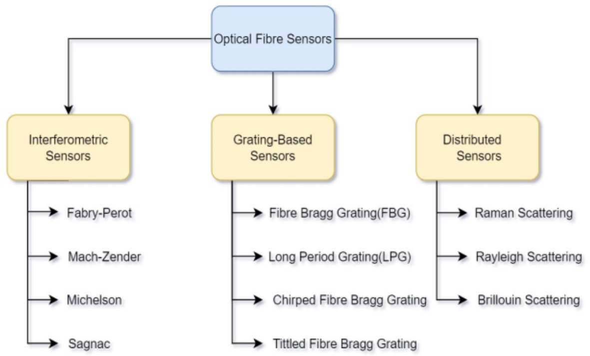


Fig.3. Types of OFS [21][24]

A. Optical sensors

Optical sensors are the devices into which a measured object or an input signal introduces modulations in some of light's characteristics in an optical system. After the input signal is detected, processed, and conditioned, an output signal is usually delivered in the electric domain. The transmitted light can be modulated by changing its frequency, amplitude, phase, or polarization. If optic technology is used in any of the processes or parts, then the optical sensor can be considered an Optical Sensor (OFS) [23]. Fig. 3 gives a classification of the major OFS types available. Table I summarizes the performances, advantages, disadvantages and companies manufacturing different types of OFS products.

III. OFS used for different parameters of SHM in aircrafts

Preventing and controlling corrosion in aging aircraft is becoming a vital responsibility. Early detection of corrosion will reduce the maintenance in turn reduction in the cost of ownership. An OFS ability to detect corrosions can be demonstrated using FBG, plastic optical fibre (POF), long period grating (LPG), etc. [26][27]. LPG multiplexed using an optical switch with a low-cost miniature spectrum analyzer and LPG with an appropriate coating to detect water or metal ions in inaccessible regions of the aircraft was proposed [28][29].

Different OFS such as FBG, Fabry-Perot, Mach-Zehnder, Michelson, and unique fibre such as hollow-core fibre, photonic crystal fibre, no-core fibre, and sapphire fibre were used for temperature measurements in aircraft. Also, a pressure-based optical fibre temperature sensor, microinterferometer-based for medium temperature, sapphire-solid-cavity for high temperature, and a new design for the thermal control system of demodulators were presented in [30][31][32]. FBG for surface strain, extrinsic fibre Fabry–Perot for steady pressure, optical fibre grating sensors for transverse as well as longitudinal strain and temperature were described in [33][34].

Fibre Optic Pressure Sensor with open optical channels was proposed in [35]. FBG was embedded into wound pressure vessels and for continuous monitoring of composite materials. The working of pressure and temperature microbending sensors suitable for use in liquid quantity measuring systems (aircraft fuel tanks) were described in [36][37]. OFS based SHM for bond line monitoring in Carbon Fibre Reinforced Polymer (CFRP) box structures, highly reliable advanced grid structures, distributed strain sensing was presented in [38] and dis-bonding locations on a typical wing spar section were developed based on a distributed sensing network and presented in [39]. Table II provides the summary of papers published on OFS used in aircrafts for structural health monitoring.

IV. Strain monitoring using FBG

Each part of the aircraft consists of a specific number of layers. Hence the orientation of fibres and forces are dependent on them. Aircraft structures are exhibited to numerous failures and damages. Failure occurs when an element or a structure is unable to withstand stresses that have been applied to it. That is why it is essential to develop a technology that can monitor internally the structure state [54][52]. The versatility of FBG sensors represents a key advantage over other technologies in the structural sensing field. FBG has the advantages of high sensitivity, lightweight, small size, strong anti-electromagnetic interference capability, corrosion resistance etc. [55][53].

FBG sensors operate and monitor transversal as well as axial strains [56] [57] in various inaccessible areas [58]. They are light weight, small size, have high sensitivity, strong anti-electromagnetic interference capability, corrosion resistance, long-term stability and durable[53] [59]. Hence embedded FBG systems can lead to reduction in inspection intervals, less maintenance cost of aircraft and further improvement in performance [60].

An FBG is manufactured by inducing a periodic variation of refractive index and the core of single-mode optical fibre via ultraviolet light, which acts as a wavelength selective mirror that reflects a narrow spectral band centered around the so-called the Bragg wavelength [61][62]. In other words, FBG is illuminated by a light source, a set of beams reflected from a set of partially reflecting planes created by the periodic core index modulation interfere with each other. The interference is destructive unless each beam is in phase with all the others. According to Bragg's law, which gives this condition, only one wavelength, that is Bragg wavelength is selected [63]. Bragg wavelength is given by, $\lambda_B = 2n_{eff}\Lambda$ where λ_B is Bragg wavelength, n_{eff} is effective refractive index, Λ is average grating period. Table III provides a summary of different papers describing the experimental works using FBG for strain monitoring of different structures.

V. Strain monitoring in different parts of the aircraft using OFS

OFS have shown good potential and can be easily embedded into or attached on a structure and are not affected by electro-magnetic fields [93]. Based on the detected data, manufacturers can develop the structural design, and owners can efficiently obtain operation and management [94].

TABLE I
OPTIC SENSOR TECHNOLOGIES FOR STRUCTURAL HEALTH MONITORING [21][23][25]

TYPES OF SENSORS PARAMETERS	FIBRE BRAGG GRATING SENSORS	FABRY-PEROT INTERFEROMETRIC SENSORS	SOFO INTERFEROMETRIC SENSORS	RAMAN OPTICAL TIME-DOMAIN REFLECTOMETRY	BRILLOUIN OPTICAL TIME-DOMAIN REFLECTOMETRY
Sensor type	Point Semi-distributed	Point	Long gauge	Distributed	Distributed
Main sensing parameters	-Temperature -Strain -Rotation -Pressure	-Temperature -Strain -Rotation -Pressure	-Deformation -Strain -Force	-Temperature	-Temperature -Strain
Multiplexing	-Quasi distributed -Wavelength division	-Parallel -Time-division	-Parallel -Time-division	Distributed	Distributed
Spatial resolution	0.1	0.1	0.1	1	1
Advantages	-Linearity in response -Accurate -High resolution -Inherent Wavelength Division Multiplexing (WDM) encoding	-High sensitivity -Accurate	-Long gauge -High spatial resolution	-Infinite sensing points -Fibre integrated	-Infinite sensing points -Fibre integrated
Disadvantages	Cross sensitivity	Single point	Low speed (10s)	-Temperature only -High cost	Cross sensitivity
Companies	Micron Optics Fibresensing	Luna Osmos	Smartec	Halliburton Co. Sensornet Ltd. AP Sensing	OZ Optics, Omnisens SA, Neubrex

A. Strain monitoring in aircraft wings

Fibre Bragg grating sensors for performing analysis on a wing of an aircraft model in time domain was induced by hammer impacts and later transformed into frequency domain. Displacement and strain mode shapes of the wing have been retrieved using frequency transfer function. Displacement modes provided by the accelerometers and strain ones provided by the FBGs sensors are agreeable [95].

Multiplexing technology of FBGs is used for aircraft wing shape measurement. Active modal analysis is essential for SHM of complex rhythmic wing structures and was found that it is a good approach to apply FBGs and strain rosette to the full-field deformation analysis of wing shape [51].

In experimental work of Ryu et al. [93], smart composite wing box was connected with 24 FBGs were arrayed in four pairs lines, where each pair had seven FBGs embedded into a single wing cell. It was tested and simulated under lift-induced bending. Three optical fibre sensor lines were embedded into the top skin, and one OFS line into the wing box's front spar. Multiplexing and multi-channeling capabilities enables the processing of information simultaneously from a large number of sensors [93].

In Kwon et al. [96], a wing load monitoring system embedded with FBG and data processing system for strain distribution and flight parameters and evaluation of wing load was incorporated on aircraft fuselage. During take-off, climb and descent, flight data analysis and banked turn are estimated with a 4.19% average error. Wing load history presented results reasonably resembling to the loading circumstances for several flight states of the aircraft [96].

Under real-time wind tunnel testing, FBGs were used to estimate dynamic strains inside a subscale wing which could identify a frequency response up to 100 Hz and had an exquisite resolution (<5 $\mu\varepsilon$) in time domain. Flutter and health of the half wing were detected and verified [97]. Surface-attached FBGs when tested under various operating conditions were simple, reliable, had good consistency, strain transfer effect, high measurement precision. Strain measurement method was used to calibrate, improve the accuracy of FBGs before use, and accuracy of the measurement of wing deformation [98]. Strain and damage of a composite wing of a solar-powered aircraft was monitored using OFS until it breakdowns. FBG sensors were attached at seven points to measure strain and acoustic emission of fracture signal using which damage occurrence and location was estimated and analyzed in [99].

FBG sensors were fitted to the surface of the test panel for the monitoring drop-weight impact tests and two periodic fatigue tests based on the aircraft's design service life in the experiment conducted by Takeda et al. [100]. By using the spectrum change of the sensor output, impact damages were detected. Barely visible impact damages could be detected because the strain change severely distorts the shape of the spectrum due to the occurrence of damages. FBG sensors have the capability for the long-term health monitoring of large-scale composite structures and development of inspection performance on large-scale composite fabrications [100].

TABLE II
SUMMARY OF PAPERS PUBLISHED ON OFS USED IN AIRCRAFTS FOR STRUCTURAL HEALTH MONITORING

REFERENCE	YEAR	TYPE OF SENSOR	EXPERIMENT HIGHLIGHTS
H.B. Liu et al.[40]	2003	Combination of polymer and silica FBG	Combination of a polymer and silica FBG gives large discrimination against temperature and strain. It provides large sensitivity and dynamic range for sensing temperature and strain changes simultaneously and independently.
S. Takeda et al.[41]	2004	FBG	The relationship between the delamination size and the form of the spectrum was found, from which the present method using small-diameter FBG sensors was found to be effective.
Ramesh Sundaram et al.[42]	2005	FBG	A strategy wherein skin-stiffener debonds can be detected using static strain measurements in conjunction with neural networks for a specified load was able to predict the damage size considerably.
NezihMrad [43]	2007	FBG	FBG sensors were used for measurement of parameters relevant to aircraft structural monitoring and smart structure. When compared FBG sensors correlated well with conventional sensor technology for temperature, static, dynamic, crack growth, and cure monitoring.
Hideki Soejima et al.[44]	2008	FBG/PZT	FBG sensors were used as sensors and piezoelectric transducer (PZT) as the generators of elastic waves. FBG sensors were able to monitor damage initiation and propagation by change in the waveform of the elastic waves in coupon specimens and structural element specimens.
Nobuo Takeda [45]	2013	OFS	Small-diameter optical fibres and their FBG sensors proved to be effective for embedment inside a lamina of composite laminates (without strength reduction) and some feasible applications in aerospace composite structures.
Toshimichi Ogisu et al.[46]	2015	FBG/PZT	Detected the elastic waves launched from PZT actuator using a high-speed and high-accuracy FBG sensor to resolve debonding and delamination at the interfaces of the laminate.
Tyler P Jones et al.[47]	2016	FBG	A modified pull-out test was set-up to obtain the interface properties of optical with polyimide or Ormocer coating embedded in 3 different adhesives.
Kohei Takahashi et al.[48]	2016	FBG	Detected damages such as delamination and debonding in aircraft composite structures and results of joint tests for the SHM system with Japan Airbus are discussed
Matthew J. Nicolas et al. [49]	2016	FBG	FBG strain measurements enabled the computation of the deflected wing shape and out-of-plane loads of the wing.
Yu Wang et al.[50]	2019	PZT	Proposed PZT sensor network with shared signal transmission wires, which could remarkably reduce the number of wires for both passive and active SHM.
Zhen Ma et al.[51]	2019	FBG	Technical characteristics and bonding technology of FBG and its advantages, disadvantages and application status for wing shape measurement was analyzed.
Karolina Bednarska et al.[52]	2020	Hybrid OFS	Discussed various opportunities of using hybrid sensors based on optical fibres to monitor composite structures, with a distinct emphasis on aircraft structures.
Yuege Zhou et al.[53]	2020	FBG	Summarized the advantages and applications, challenges and discussed future development trend of damage monitoring based on FBG and smart coating synthesis.

1) Strain monitoring in aircraft flaps

An experiment by Durana et al. [101], a plastic optical fibre-based sensor that relies on measuring the phase shift that occurs between two sinusoidal modulated light signals was used for elongation measurements in an bent aircraft flap. Besides, a comparison of POF sensor and the camera-based reference system used for validating the response of the POF was conducted. The high degree of repeatability (1 cycle/40 s, 1 cycle/20 s, and 1 cycle/10 s) and lack of hysteresis of the sensor signal recognized in individual movements and cyclical-type movements at different velocities.

2) Strain monitoring in aircraft spoiler

In Bergmayr et al. [102], Airbus A-340 spoiler was used for strain measurements along zero-strain trajectories for monitoring debonding initiation and propagation at the edge of the spoiler model utilizing numerical and experimental summary. A debonding of the top face layer at the trailing edge was considered. A digital image correlation (DIC) system was used to record strain and deformations. Numerical finite element method (FEM) investigation was conducted to estimate zero strain trajectories

TABLE III
SUMMARY OF DIFFERENT EXPERIMENTS USING FBG FOR STRAIN MONITORING

YEAR	AUTHOR	STRUCTURE	EXPERIMENT HIGHLIGHTS
2000	Martin Schroeck et al. [70]	Rock bolts	An FBG sensor was attached to the surface of the rock bolt. A slightly steeper inclination than the neutral angle was to be elongated in an expected ratio to the bolt's overall elongation. This ratio shifts while the bolt was being elongated.
2001	Kin-Tak Lau et al.[71]	Composite-strengthened concrete	Single- and multiplexed-point strain measuring methods were used to determine strains. Frequency modulated continuous wave method was used to demodulate the response signals from the optical fibre.
2001	Kin-Tak Lau et al.[72]	Reinforced composites, Concrete beams	Evaluation of differential strains between the bare and host material with various adhesive thickness and modulus of the protecting coating of the embedded FBG sensor.
2001	Shigenori Kabashima et al. [73]	Satellite	An FBG sensor system in a space environment simulated in a thermal vacuum chamber was defined. Optical fibre connector, FBG sensor system, and detection of damage in composite laminate were incurred.
2008	Wonseok Chung et al.[74]	Concrete box railway girder	Involved dynamic characteristics identification using a digitally controlled exciter and measurement of the nonlinear static behaviour until failure.
2008	S´ergio R. K. Morikawa et al. [75]	Flexible oil and gas lines	Alternative to electrical sensing technologies. Collar instrumented with FBG sensors demonstrated great sensitivity to variations in riser external diameter during laboratory tests.
2008	S.H. Eumo et al.[76]	Wind turbine blade	Resin flow front with the strain changes within the gauge length of FBG sensors was measured. Cure process, quality assurance and maintenance were controlled using sensors.
2009	D. Karalekas et al. [77]	Cylindrical epoxy specimen	Hygrothermal aging on the axial strains in a cylindrical epoxy specimen, moisture retention and its impacts on swelling and interface damage were investigated.
2010	Eannot Frieden et al.[78]	Cross-ply carbon-epoxy composite plates	The fast interrogation system for FBG sensors for monitoring dynamic internal strains, damage, modal analysis, locating an impact event when several FBG sensors were used and discussed.
2010	Hong-Hu Zhu et al. [79]	Dam	FBG for real-time monitoring of internal displacements. Deformation mechanism and failure pattern of model dam were studied.
2011	Agis Papantoniou et al. [80]	Composite structures	Composite specimens and patches with embedded FBGs were manufactured to online monitor SHM of aeronautical materials and typical repairs in metallic structure.
2012	Shin-ichi Takeda et al. [81]	CFRP stiffened panels	Discussed methods of monitoring low velocity impact events using FBG sensors. Damage growth, difference of buckling behaviours between panels were evaluated.
2012	Carlos Rodrigues et al. [82]	Centenary metallic bridge	Monitored strains in steel bridges to assess structural behaviour during structural rehabilitation. Strain levels and distributions, supported the assessment and validation of main assumptions adopted in the structural design.
2012	Hyung-joon Bang et al. [83]	Wind turbine tower	High-speed FBG sensor system was used for shape estimation of wind turbine tower under dynamic loads.
2013	X.W. Ye1 et al. [84]	Railway Tunnel	Discussed safety monitoring during railway tunnel construction. Investigated real-time temperature measurement method of the frozen soils during freezing construction of a metro-tunnel cross-passage.
2014	D. Kang et al. [85]	Smart Railroad-Gauge	Monitoring system in the gauge change facilities were developed using FBG and graphic user interface (GUI) software.
2014	Qingmin Hou et al. [86]	Natural gas pipeline	Detected negative pressure wave signals caused by leakage. Monitored hoop strain of a pipeline to detect negative pressure wave signals without EMI.
2014	Guo-Wei Li et al. [87]	Pretensioned high strength concrete pipe piles	Dealt with monitoring and performance evaluation of a PHC pipe pile under hydraulic jacking. Axial force and average shear stress on the pile surface were calculated using measured axial strain.
2015	Wei Shen et al. [88]	Hull structure	Strain sensing was conducted through the tensile machine and compared with the results of electric resistance strain. Strain rosette structure had a good sensitivity, resilience, and long-term stability.
2015	Rui Cheng et al. [89]	Remote adaptive strain monitoring	Easy multiplexing, stability against random perturbations, self-adaptation to temperature. Higher sensitivity compared to common wavelength modulated optic sensors.
2016	Hong Cheng et al. [90]	Geotechnical Health Monitoring	Monitoring of several key geotechnical structures, including soil nail systems, slopes, piles, steel bars, and different types of small tubes.
2017	Weijie Li et al. [91]	Monitoring Concrete Deterioration	Corrosion monitoring of a steel reinforced mortar block through combined acoustic emission and strain measurement. Correlation between acoustic emission activity and expansive strain.
2018	Xiao Zhou et al. [92]	Wheel tread defect detection	Large quantity of wheel inspections, remote monitoring, wheel defect detection method can automatically identify rail responses in connection with excitation generated by each wheel.
2019	Li Sun et al. [92]	Soil strain monitoring	Desensitization method to develop a wide-range FBG sensor for extra-large strain monitoring. Sensor’s fatigue properties were studied and field experiments were carried out.

(ZST) for pristine structure and variations in strain states caused by the damage. To detect monitor debonding propagation strain sensors were optimally placed along these ZST. This approach has a high potential for monitoring, and also the results are evaluated using distributed continuous OFS or FBG sensors placed on the surface to attain greater accuracy.

B. *Strain monitoring in aircraft fuselage*

In the experimental work of Menendez et al. [103], FBG sensors were surface bonded on two of the 3 blade-stiffened CFRP panels and are embedded into the third panel's stiffener webs. Strain distribution in the stiffener web and in the skin panels, bucking onset and post-buckling behaviour were clearly detected. Embedded FBG sensors do not significantly compromise the tensile characteristics of the host material and they show similar time dependent behavior like conventional extensometer exhibited signals when they were subjected under tensile tests [103]. In Wada et al. [104], optical frequency domain reflectometry (OFDR) which consists of a long-length FBG, was used to obtain strain data as a distributed profile. Fuselage stringer and bulkhead structural responses were monitored during taxiing, landing, take-off, and numerous other maneuvers. Strain amplitude and characteristics of the structural responses during operation and condition of aircraft in accordance with the different maneuvers were studied [104].

In [103], system design, implementation and validation of a strain and damage monitoring system for CFRP fuselage stiffened panels based on FBG were described. In [104], mechanical testing and validation of the panels were described.

According to [105][106] a design of the fuselage panel, monitoring system, the embedment of fibre sensors in the panel during manufacturing and the impact testing were inspected using C-scan to identify impact damage at various location. FBGs captured changes in buckling modes of panel. Mechanical tests comprised three load-scenarios: compression to failure of undamaged panel, impacted panel and of impacted, fatigued panel.

C. *Strain monitoring in aircraft landing gear*

Fibre Bragg Grating sensors arrays of six and four gratings were integrated in various locations of the composite item, including a region with a huge bending radius. Load condition was analyzed using FEM for optimizing localization of FBG sensors. These were capable of detecting unusual function as early warning system. They also demonstrated capability to recognize breaking of the item when the early warning was neglected [107].

FBG strain sensor was integrated on main and nose gear in a linear and tri-axial configuration. Gears were subjected to hydraulic press. Load condition were obtained from numerical analysis and were exposed to several lab tests. Strain variations touching several hundreds of $\mu\varepsilon$ were recognized in correspondence of the maximum take-off weight on nose landing gear. Monitoring strain along horizontal axis was an alternative for load monitoring both on the nose and main landing gears [108].

In another experimental work, load was measured in vertical direction and drag was measured in a horizontal direction using optic load sensor for monitoring load in a landing gear component. The arrangement was in such a way that they determine the direction of bend and load on the component wherein load can be separated out into vertical and drag components [109].

D. *Strain Monitoring in Aircraft Outlet Guide Vane.*

Results of testing outlet guide vane were obtained from the indications of sensors on the principle of FBGs placed on the surface and compared with mathematical modelling results in the software package ANSYS by the finite element method. By applying FEM using ANSYS (Analysis System) workbench nonlinear contact 3-dimensional problem of mechanics of inhomogeneous media was solved [110]. Outlet guide vane made of strong carbon cloth on epoxy binders was monitored using OFS, which are capable of self-diagnosing and forecasting the resource of work. Calculations and results show a good convergence when optical fibre sensors were located in zones with a low gradient of deformation [111].

VI. CONCLUSION

Structural health monitoring helps identify, observe, collect, and analyze data related to performance deterioration of structures. SHM of aircraft is required since there is an increase in aircraft production, and aging of aircraft is subsequently increasing. It helps in locating when the damage occurred precisely in real-time. Examinations and inspections are executed using several technologies like wireless sensors, piezoelectric transducers, MEMS, optical fibre, etc. Optical fibre sensor is a mature technology since they are small in size, lightweight, embedding capability, also immune to EMI and corrosion thereby they can monitor several parameters such as temperature, pressure, vibration, corrosion, and strain-induced in the structures. Several optical fibre sensors such as interferometric sensors, distributed sensors, and grating-based sensors are generally used to monitor the structural health of aircrafts. Bragg grating are inexpensive, reliable, highly sensitive and immune to electromagnetic and radio interference. They can be used in hazardous environments, multiplexed, and complexity of wiring can be reduced by placing a multitude of sensors along a single. Finite element method was found to be effective for load conditioning. Monitoring of wings, flaps, spoilers, fuselage, outlet guide vane, and landing gear were discussed. Hence more effort is still required in investigating the accurate positions of damage in real time measuring of strain, where the sensors can be placed in the structure and response under complex deformation and can be considered for future scope.

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