Proposal for Structural Health Monitoring of a Thin Aluminum Plate with Thickness Loss

D R Louzada[1], A M B Braga[2], P M P de Gouvêa[2] and C R H Barosa[1]

[1] Postgraduate Programme in Metrology, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro,RJ, 22451-900, Brazil

[2] Mechanical Engineering Department, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro,RJ, 22451-900, Brazil

louzada@puc-rio.br

Abstract. Different methodologies are employed in structural inspection tests, aiming at certifying quality while considering the fulfilment of project requirements and/or specifications. Their significance lies in their ability to detect or prevent potential irregularities, which may manifest in various forms, such as structural weakening due to fatigue, cracks from repetitive stress, delamination in composite materials, and corrosion. In this context, there has been an increasing emphasis on developing and implementing methodologies enabling the investigation of what has been conventionally referred to as Structural Health Monitoring (SHM). The present study addresses this subject, focusing on an experimental investigation of thickness loss in a thin aluminium plate monitored by fiber optic sensor networks. The experimental tests show measurements with uncertainty below 2 % more important, that the static load provoke deformation patterns that can indicate the presence of such defect.

1. Introduction

The interest in implementing Structural Health Monitoring (SHM) methods aiming at both detection and characterization of different types of damage has been observed in recent years, and it is increasing nowadays [1-4]. Indeed, corrosion processes are among the events that significantly affect the integrity of metallic structures, leading to substantial damage. Biezma and Cristobal (2005) showed that countries like Japan and the USA spend approximately 5 % of their gross domestic product on issues related to structural corrosion [5].

While antioxidative products provide some corrosion protection, over time, such procedures may lose effectiveness, and their detection can become insufficient and costly. Indeed several approaches are facing the problem from different perspectives, and it has been observed many research on corrosion detection and damage characterization using techniques of non-destructive tests (NDT) that indicate good results on structural integrity assurance [6-10].

A corrosion process is associated with a local thickness loss in the affected structure. When corrosion occurs in a thin plate, the change in plate thickness alters the local distribution of stresses and, consequently, the pattern of surface deformations associated with external loads. Thus, recording these pattern alterations provides essential information for structural characterization.

In this scenario, Structural Health Monitoring (SHM) methods are well suited to the task as they advocate the investigation of different physical structure's characteristics. SHM, can be defined as the implementation of NDT technics to monitor the stat of a structure, through a sensor network distributed over a specific structure. These sensors continuously measure a key variable, searching for slight signal changes arising from modifications in the physical properties, effectively functioning as a nervous system for the structure.

To avoid excessive loading on the structure while not restricting the extent of the examined area, sensors based on Fiber Bragg Gratings (FBG) become a very attractive alternative [11-19]. FBG sensors are particularly interesting given their characteristics such as reduced dimension, its multiplexing potential (that responds with frequency modulation) and are immunity to electromagnetic interference. For instance, Chan et al. (2006) used a network of Bragg sensors to monitor a suspension bridge, obtaining excellent results compared to the existing system in the structure [20].

An FBG sensor is a periodic variation in the refractive index in a small longitudinal region of the optical fiber core (10 mm). This periodic variation acts as a wavelength-selective filter, allowing specific wavelengths of light to be reflected while transmitting others. In other words, when a light beam is transmitted through the fiber, a specific component of the electromagnetic radiation is reflected. The reflected electromagnetic is characterized by a wavelength (Bragg wavelength, λ_B) proportional to the spatial period of the modulation (Λ) inscribed in the optical fiber. In a simplified way, one can represent the Bragg wavelength by equation 1, which presents a relationship between the refractive index modulation (Λ) and the effective refractive index in the fiber core (n_e).

$$\lambda_B = 2.\ n_e\ .\ \Lambda \tag{1}$$

There are various ways to implement SHM systems capable of detecting the presence of structural damage. Salawu (1997) reviewed damage detection methods using vibrational monitoring of structures, employing the natural frequency analysis as a reference parameter [21]. Worden et al. (2000) investigated the problem of damage detection through statistical methods [22]. Silva et al. (2003) focused on identifying non-apparent corrosion in aeronautical aluminium structures through ultrasonic wave analysis using a Mach-Zehnder interferometer [23]. Ngo Le et al. (2023) examined how corrosion affected the vibrational properties at the ends of steel plate girder bridges [24].

This paper will present an experimental investigation of a thickness loss in a thin aluminum plate, as part of a SHM proposal. This work is structured into 4 sections. The first section presents the introduction. Section 2 describes the methodology used for conducting the experimental tests, while Section 3 presents the results and discussions. Finally, the conclusion is presented in Section 4, along with indications for future work.

2. Methodology

Structural Health Monitoring (SHM) may require investigations of mechanical patterns of the structure when subjected to external (static or dynamic) loads. In the present study, two cases (non-defect and defect simulated) were investigated:

I. A thin aluminium plate with dimensions equal to 400 mm, 130 mm and 3 mm (length, width and thickness), representing a non-defect case;

II. A similar thin aluminium plate (the same dimensions) but with a square thickness loss with an area of 32 mm^2, representing a defect case. This thickness loss was obtained with a mechanical machining process that removed its thickness to 1.65 mm.

Figure 1 illustrates a photograph of the thin aluminium plate as a structure to be monitored. It can be observed the region where the machining process simulates a corrosion effect by removing a portion of the material, resulting in a reduction of aluminium thickness.

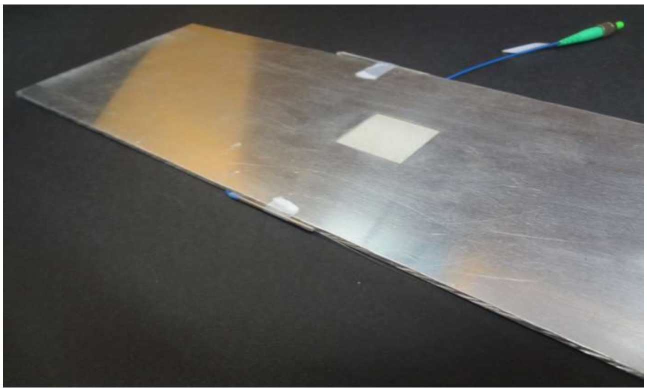

Figure 1. Thin aluminium plate with a thickness loss of 1.35 mm (45 % of the original thickness), caused by the mechanical machining process

The mechanical properties of the thin aluminium plate used for the experimental test are depicted in Table 1.

Table 1. Thin aluminium plate parameters.

Parametrer	Symbol	Numerical Value
Length	L1	400 [mm]
Width	L2	130 [mm]
Thickness	L3	3 [mm]
Young's Modulus	E	66,6 Gpa
Poisson's Coefficient	N	0,3
Density	μ	2700 kg/m^3
Material	AL 6351-T6	-

To monitor the aluminium plate and obtain records of the surface deformation when it was subjected to an external load, a set of 4 Fiber Bragg Grating sensors (FBG) were attached to its surface.

The optic fiber with the FBGs was glued on one of the surfaces of the aluminium plate without defect (case I) and at the surface opposite the one with thickness loss (case II).

The Figure 2 shows a schematic drawing of the 4 FBGs distributed into an optical fiber array.

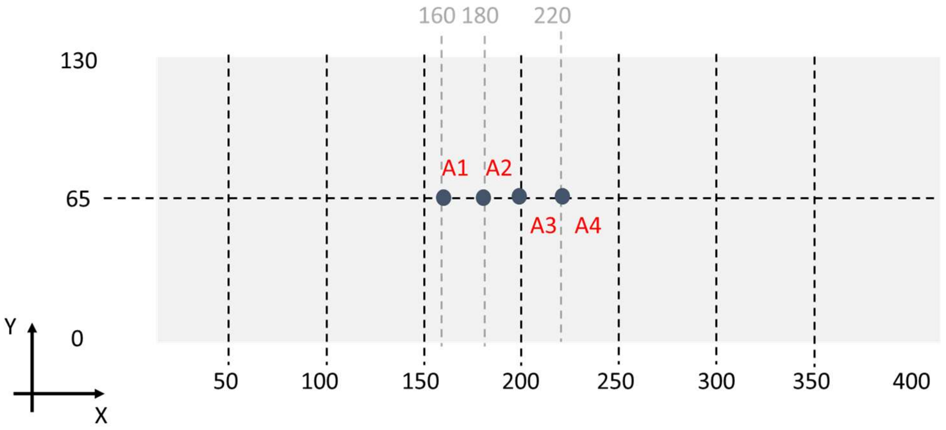

Figure 2. Schematic drawing of the FBG sensors' location.

The experiment involved a tensile test at PUC-Rio University's mechanical laboratory. The surface deformations on the aluminium plate were monitored by reading the FBG sensors (Figure 3 (a)) while an adjustable tensile force was applied. The measurement procedure consisted of injecting light with a wide spectral band at the optic fiber, which, upon interacting with the Bragg grating (attached to the structure being monitored), reflects a portion of its intensity with the Bragg wavelength. Analyzing the reflected or transmitted wavelength determines the deformation experienced by the optic fiber, therefore, the structure. The signal variation occurs due to the elongation or contraction of the fiber when subjected to tension or temperature variation (which leads to a change in the value of Λ).

Since the FBG sensors' response depends on the deformation caused by mechanical loading and thermal variations, all tests were conducted at a constant laboratory temperature (25 °C).

After affixing the sensors to the aluminum plate, each optical fiber array was connected to a channel of a portable optical measurement unit (BraggMETER), as seen in Figure 3 (b). The experimental test was conducted using a traction machine, where one end of the aluminum plate was fixed while the other was pulled. Figure 3(c) shows a close-up view of the aluminium plate during the tensile test.

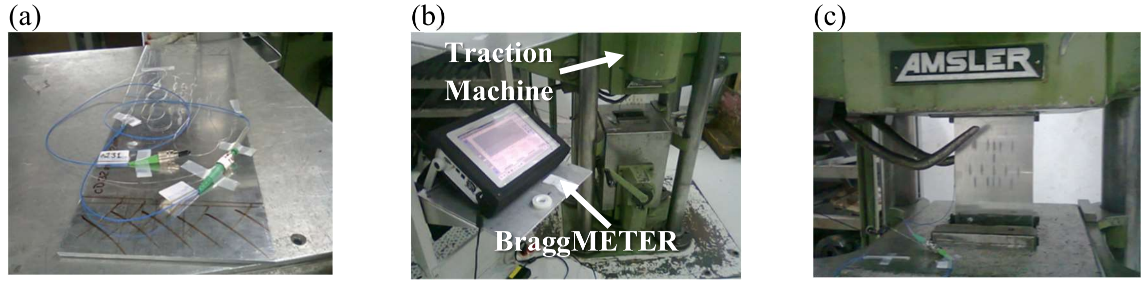

Figure 3. (a) Thin aluminium plate instrumented with FBG sensors; (b) the plate fixed to the traction machine with the sensors connected to BraggMETER; and (c) a close-up view of the aluminium plate during the tensile test

The tensile test was conducted by applying a variable force to the aluminium plate while the BraggMETER recorded the FBG signals. The procedure involved incrementally increasing the force (step of 400 kgf) until a predefined value was reached: tensile forces equal to 400 kgf, 800 kgf, 1200 kgf, and 1600 kgf (or in SI units, 3 922.66 N, 78 45.32 N, 11 767.98 N, and 15690,64 N).

Once the applied tensile force on the aluminium plate matched one of the 4 defined magnitudes, the traction machine stopped varying the force, keeping it constant for a few seconds. This process was repeated until the force reached 1600 kgf, at which point the reverse process was carried out, reducing the tensile force until zero.

3. Results and Discussion

The measured records were saved in a ".txt" file and then plotted in a MatLab environment. Figure 4 displays the tensile test results for the 4 FBG sensors fixed in different locations at different loads. The graphic shows the increase of the deformation measured as the tensile force varies and stands constant when the tensile force is left fixed.

It can be observed that the deformation measured by all 4 FBGs in the plate without defect (case I) are very similar to each other (Figure 4a), while a very different pattern is observed at the plate with the thickness loss (Figure 4b). These results indicate a potential use of surface deformation as an important mechanical propriety for detecting defects such as corrosion in metallic structures.

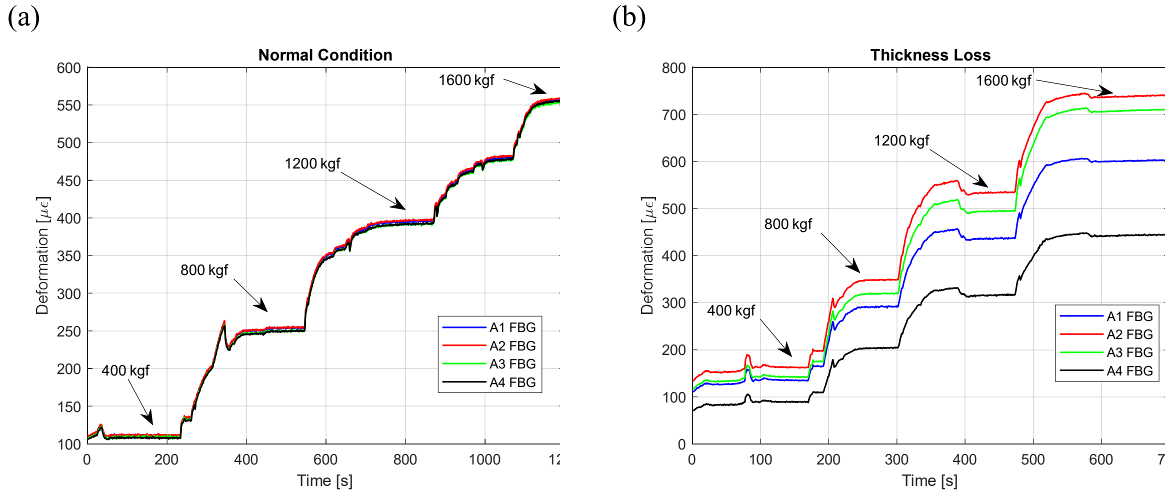

Figure 4. Deformation data measured by the 4 sensors fixed on the surface of the aluminum plate during the tension test; (a) show the case without thickness loss and (b) with thickness loss.

Table 2 shows the information recorded by the 4 sensors and their coordinates (x, y) in the aluminum plate (case II, with thickness loss).

Table 2. Experiment's data.

	Sensor	X [mm]	Y [mm]	400 [kgf]	800 [kgf]	1200 [kgf]	1600 [kgf]
Strain [με]	A1	65	160	135,8	290,3	436,3	601,8
	A2	65	180	163,4	347,1	433,8	739,2
	A3	65	200	142,9	318,1	494,1	709,1
	A4	65	220	89,5	202,6	315,8	433,5

As expected of a non-destructive test, the deformations obtained by the sensors on the aluminium plate as a function of applied tension showed linearity. This effect can be observed in Figure 5, which displays the response of the A4 FBG sensor to the variation in tension applied to the aluminium plate.

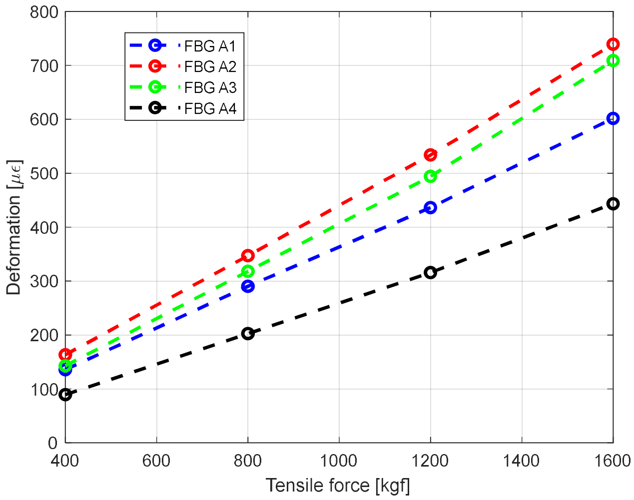

Figure 5. The linear relationship between the surface deformation measured by the 4 FBG sensors and the loading applied to the aluminium plate with thickness loss.

Is also interesting to note in Figure 5 that as each FBG sensor is fixed in a different location, it brings light to the deformation pattern at the plate surface. This result points out two hypotheses: (i) the deformation pattern is influenced by the proximity of the thickness loss (or a corrosion process), and (ii) there is no need for a data baseline (pattern without defect) to detect or characterize a corrosion process.

It was also calculated the uncertainty of the measurements. Table 3 depicts the results of the expanded uncertainty of each FBG sensor at the different load sets. For the uncertainty calculations, was considered a confidence interval of 95.45 % of a normal distribution.

Table 3. Expanded uncertainty of the FBGs sensors (case with thickness loss)

		Tension force			
	Sensor	400 [kgf]	800 [kgf]	1200 [kgf]	1600 [kgf]
U [με]	A1	1,47	1,52	1,30	1,15
	A2	1,86	2,12	0,96	1,12
	A3	1,60	2,01	0,84	1,08
	A4	1,74	1,47	1,00	1,21

The results show adequate uncertainty in the experimental texts, with less than 2 % for the load of 400 kfg and near than 1 % for the other loads (Figure 6).

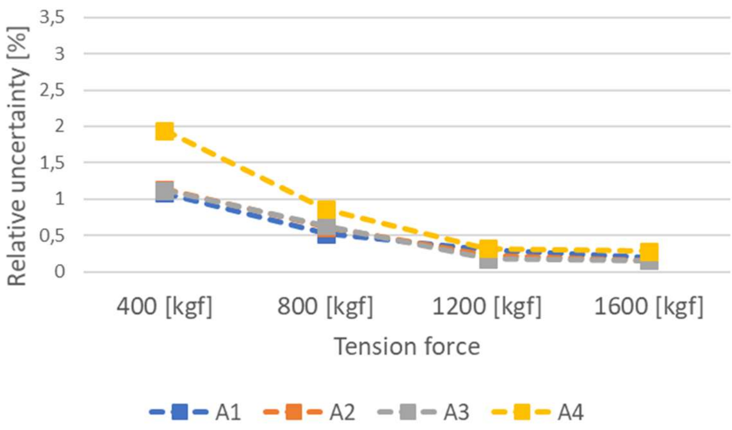

Figure 6. Uncertainly variation with the tension applied.

Since the present study, the FBG sensor network had a limited number (only 4 FBGs), it wouldn't be practical to try to establish a surface's deformation map pattern to detect and characterize the thickness loss. Instead, as the FBG sensors are aligned to the defect (passing through it), it is relevant to observe how the deformation pattern of the segment formed by the sensor line appears (Figure 7). It is clear that when there is no defect in the structure (aluminium plate), it is observed a pattern of a similar deformation in all 4 sensors (Figure 7a). The same is not observed when there is a thickness loss (Figure 7b).

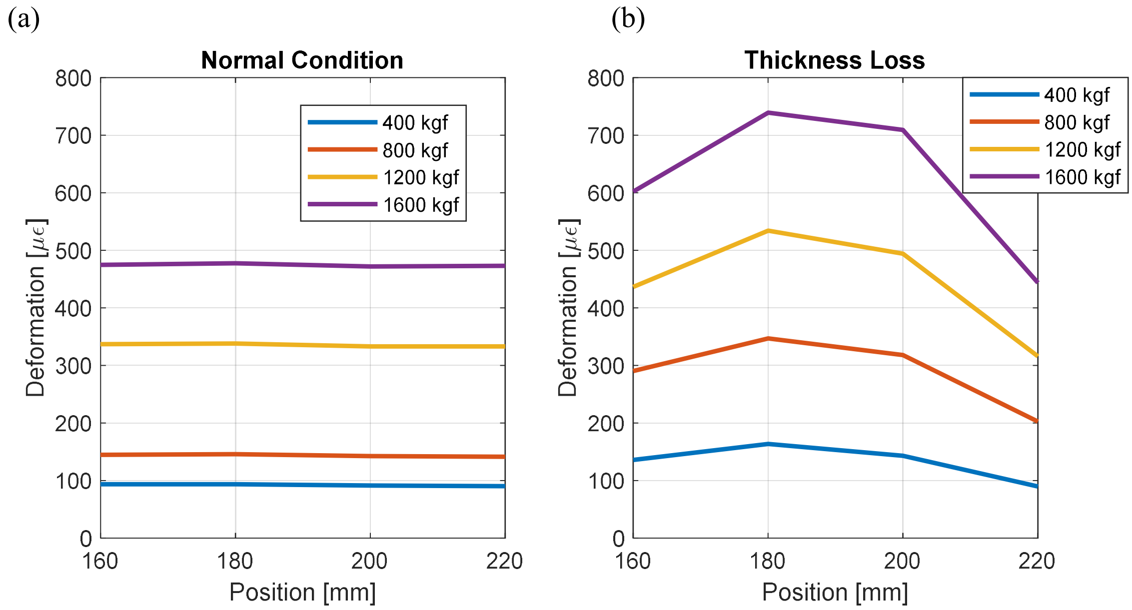

Figure 7. Deformation pattern of (a) the case without thickness and (b) the case with thickness loss.

These findings lead our team to speculate that it is possible to use a fine sensor network covering the surface of a structure to monitor the existence and progress of a thickness loss.

4. Conclusion

An FBG sensor network instrumentation was carried out on a structure consisting of a thin aluminium plate to monitor its structural health behaviour.

Measurements were taken with different tensions to assess how surface deformation patterns in the aluminium plate behaved. It was observed that the deformation patterns can indicate potential damage, such as thickness loss.

The results indicated no need for baseline data when a constant load is presented. The deformation pattern formed when there isn't a defect is easily predicted and is totally different when there is a defect like a thickness loss.

Future work will investigate different and more practical loads to be applied to a structure. Specifically, there is an interest in investigating dynamic loads formed by actuators like piezoelectric ones.

Acknowledgements

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) - Financing Code 001.

References

[1] Dan L, Jia-Hao N, Hao W, Jia-Bao Y, Chen-Xun H and Peng S, Damage location, quantification and characterization of steel-concrete composite beams using acoustic emission, 2023 *Engineering Structures*, **283** 115866.

[2] Afshin S and Tamara N, Damage localization and characterization using one-dimensional convolutional neural network and a sparse network of transducers, 2022 *Engineering Applications of Artificial Intelligence*, **115** 105273.

[3] Chiwoo P, Tang J and Tang Y, Aggressive data reduction for damage detection in structural health monitoring, 2010 *Strucural Healht Monitoring*, **9** 59-74.

[4] Farrar C R, Doebling S W and Nix, D A Vibration–based structural damage identification, 2001 *Phi. Trans. of the Royal Soc. of London. Series A*: Math., Phys. and Engineering Sci, **359** 131-49.

[5] Biezma M V and San Cristobal J R, Methodology to study cost of corrosion, 2005 *Corrosion engineering, sci. and tech.*, **40** 344-52.

[6] Shang L, Zhang Z, Tang F, Cao Q, Pan H, and Lin Z, CNN-LSTM Hybrid Model to Promote Signal Processing of Ultrasonic Guided Lamb Waves for Damage Detection in Metallic Pipelines, 2023 *Sensors*, **23**, 7059.

[7] Wiciak P, Polak M A and Cascante G, Nondestructive Evaluation of Damage in GFRP Bars Using Ultrasonic Guided Waves, 2021 *Journal of Composites for Construction*, **25**, 04021055.

[8] Kilic G and Caner A, Augmented reality for bridge condition assessment using advanced non-destructive techniques, 2021 *Struc. and Infrastructure Eng.*, **17**, 977–89.

[9] Pidaparti R, Aircraft structural integrity assessment through computational intelligence techniques, *2006 Struc. Durability & Health Monitoring*, **2**, 131-47.

[10] Worden K and Dulieu-Barton J M, An overview of intelligent fault detection in systems and structures, 2004 *Structural Health Monitoring*, **3** 85-98.

[11] Betz D C et al., Structural damage location with fiber Bragg grating rosettes and Lamb waves, 2007 *Structural Health Monitoring*, **6** 299-308.

[12] Grossmann B G and Huang L, Fiber optic sensor array for multi-dimensional strain measurement, 1998 *Smart Materials and Structures*, **7** 159-65.

[13] Satori K et al., Development of small-diameter optical fiber sensors for damage detection in composite laminates, 2000 *In: Smart Struc. and Materials: Sensory Phen. and Meas. Instrmentation for Smart Struc. and Materials,* ***3986*** 104-11.
[14] Zhao W and Claus R O, Optical fiber grating sensors in multimode fibers, 2000 *Smart Materials and Struc.*, **9** 212-16.
[15] Studer M and Peters K, Multi-scale sensing for damage identification, 2004 *Smart Materials and Struc.*, **13** 283-296.
[16] Betz D C et al., Multi-functional fibre Bragg grating sensors for fatigue crack detection in metallic structures 2006 *Proc. of the Inst. of Mech. Eng. Part G: J. of Aerospace Eng.*, **220** 453-61.
[17] Kim M, A smart health monitoring system with application to welded structures using piezoceramic and fiber optic transducers, 2006 *J. of Intelligent Mat. Sys. and Struc.*, **17** 35-44.
[18] Ansari F, Practical implementation of optical fiber sensors in civil structural health monitoring, 2007 *J. of Intelligent Material Sys. and Struc.*, **18** 879-889.
[19] Zhou G and Sim L M, Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors-review, 2002 *Smart Materials and Struc.*, **11**. 925-39.
[20] Chan T et al., Fiber Bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation, 2006 *Eng. Struc.*, **28** 648-659.
[21] Salawu O S, Detection of structural damage through changes in frequency: a review, 1997 *Eng Struc.*, **19** 718-23.
[22] Worden K, Manson G and Fieller N R J, Damage detection using outlier analysis, 2000 *Journal of Sound and vibration*, **229** 647-67.
[23] Silva M Z, Gouyon R and Lepoutre F, Hidden corrosion detection in aircraft aluminum structures using laser ultrasonics and wavelet transform signal analysis, 2003 *Ultrasonics*, **41** 301-05.
[24] Hayashi G, Oura R, Hiraoka A and Yamaguchi T, Vibration characteristics and load-carrying capacity of multiple steel plate girder bridges with corroded girder ends, 2023 *Struc. and Infrastructure Eng.*, 1-14.