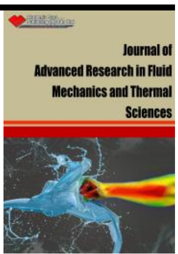
Penerbit
Akademia Baru

Journal of Advanced Research in Fluid
Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



# Surface Strain Measurement on Pressurized Thick-Walled Pipe by Fiber Bragg Grating Sensor and Strain Gauges

M. S. N. A. Adhreena[1], Z. M. Hafizi[1,*], E. Vorathin[1]

[1] Advanced Structural Integrity and Vibration Research (ASIVR), Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang (UMP), 26600 Pekan, Pahang, Malaysia

**ARTICLE INFO**

***Article history:***
Received 28 December 2020
Received in revised form 8 May 2021
Accepted 9 May 2021
Available online 5 July 2021

**ABSTRACT**

The evaluation of circumferential and longitudinal strain is significant in a pipeline integrity monitoring. Through this study, fiber Bragg grating (FBG) sensors and resistance foil strain gauges (RFSG) sensors were applied to monitor and measure the circumferential and longitudinal strain on a thick-walled pressurized pipe. The experimentation was conducted on 0.6 m-long A53 seamless carbon steel pipe subjected to uniform internal pressure by using a hydro pressure test pump ranging from 0 to 5 MPa. The result reveals the excellence repeatability of the FBG sensor during loading and unloading of the pressurized pipe if compared to the RFSG sensors, with the percentage error varies from 1.08% to 6.17%. In term of linearity, FBG sensor exhibits low percentage error with 0.12% and 3.89% for longitudinal and circumferential strain respectively, while the RFSG sensors have a significant percentage error with 0.33% and 0.03%, respectively. These results confirm the stability of FBG sensor to be considered as a realistic sensor instrumentation for pipeline health monitoring.

***Keywords:***
Fiber Bragg Grating (FBG); thick-walled pipe; surface strain; internal pressure

## 1. Introduction

Pipes and pressure vessels have been broadly utilized for decades and becoming a source of importance in engineering technology as a medium to convey and store high-temperature liquids and gases [1-3]. They have a multitude of applications in industry including power plants, oil refineries, submarine technology, aircraft fuselage as well as gas reservoirs. These pressure vessels must be designed and constructed to satisfy specified integrity requirements. In oil and gas infrastructures, the critical evaluation of the internal pressure of pipelines is exceptionally crucial with regard to their integrity, safety and cost-effectiveness. A rupture in a pipeline will lead to a serious environmental damage and suffer huge losses if leaks are not immediately detected. Corrosion and stress in the pipeline are two major contributions to the leakage accidents in a pipeline industry and thus monitoring these parameters had become an important research topic [4]. A pipeline is considered to be a pressure vessel with comparatively stable inner pressure during a long-

---

[*] *Corresponding author.*
*E-mail address: hafizi@ump.edu.my*

https://doi.org/10.37934/arfmts.84.2.19

term service operation. Thus, the indirect leaking monitoring method can be designed by measuring the effects of changes in internal pressure. With an increase of internal pressure, the circumferential and longitudinal strain can be measured on the outer surface of the pipeline. In addition, the local corrosion of pipeline can also be detected as corrosion rate, that will reduce the wall thickness of the pipe, which in turn causing the circumferential strain is gradually increased [5]. Following these factors, a circumferential and longitudinal strain measuring procedure utilizing FBG sensor was deployed to predict the leakage due to changes of internal pressure.

In the last decade, the popularity of optical fibers for real-time structural health diagnosis has expanded significantly. Optical fiber sensors such as locally high-precision fiber Bragg grating (FBG) sensors dominating the engineering field as the most promising sensing technology with its great features for multiplexing capability, lightweight, immune toward electromagnetic interference (EMI) and radio frequency interference (RFI) fields thus applicable in harsh conditions [6-8]. Understandably, for a larger surface area of the structure will require innumerable sensors for SHM application. On the contrary, FBG sensor with multiplexing capability had presented these qualifications when numerous sensors can be multiplexed and combined together to form one single optical fiber [9, 10]. Moreover, this innovative sensor can provide a good automated sensing measurement, also durability and reliability, thus improve the measurement quality in contrast to previous conventional sensors that are combining both heuristic method and visual observation for validating the behaviour of structure [11]. This intelligent behaviour of FBG sensor had drawn great interest from many in-field researcher's community and also engineering professionals to cope with the problem more effectively [12].

In this study, the FBG and strain gauge sensors were installed on the pipe to measure the surface strain subjected to an internal pressure. Based on the advantages of FBG sensors in distributed strain measurement, FBG sensor is selected as a suitable candidate for real-time pipeline monitoring. In the meantime, a strain gauge was used as a comparative device element since it is already established in structural health monitoring. An experimental study was carried out to evaluate the behaviour of both sensors and compare it with theoretical values. In the end, conclusions were drawn on the behaviour of the both sensors to measure a surface strain on the pipe vessel based on the internal pressure impact.

## 2. Methodology

### 2.1 Pipe

The theoretical calculations of longitudinal and circumferential strains induced in the carbon steel pipe test were calculated by using two-step process. In this case, thick-wall theory is derived from theory of elasticity since the ratio between the inner radius of the pipe and the thickness of the wall is less than 10 ($\frac{r_i}{t} \leq 10$) [13, 14]. Firstly, the stresses act upon the principle axis were determined by using the formula of Lame's theory [15]

$$\sigma_L = \frac{P_i {r_i}^2 - P_o {r_o}^2}{{r_o}^2 - {r_i}^2} \quad \text{and} \quad \sigma_C = \frac{P_i {r_i}^2 - P_o {r_o}^2}{{r_o}^2 - {r_i}^2} + \frac{(P_i - P_o) r^2 {r_i}^2}{({r_o}^2 - {r_i}^2) r^2} \tag{1}$$

where $\sigma_L$ and $\sigma_C$ are the longitudinal and circumferential stresses respectively. $P_i$ is the internal pressure applied onto the pipe, $P_o$ is an outside pressure which in this case is assume $P_o = 0$, $r_i$ is the internal radius of the pipe, $r_o$ is an outside radius of pipe and $r$ is the radius at point of interest which $r = r_o$ since the outer strain surface is validated in this experiment. From the above stresses calculations, the strains output can be calculated in the next step by using these formulas [16]

$$\varepsilon_L = \frac{1}{E}(\sigma_L - \nu\sigma_C) \tag{2}$$

$$\varepsilon_C = \frac{1}{E}(\sigma_C - \nu\sigma_L) \tag{3}$$

where $\varepsilon_L$ and $\varepsilon_C$ are the longitudinal and circumferential strains respectively, $E$ is the Young's modulus and $\nu$ is the Poisson's ratio of the pipe vessel.

In this experiment, a 0.3 m-long 4-inch pipe is designed consisting two seamless A53 carbon steel pipe, each pipe is welded to a steel flange ANSI B16.5 by using a fillet weld at one end while the other end is weld to a rectangular plate. Both flanges that used eight bolted joints evenly distributed throughout the round steel flanges are connected using the bolts that are tightened to 50 Nm torque. The pipe has an external diameter of 114.3 mm, an internal diameter of 102.36 mm and a nominal wall thickness of 6.10 mm. Their material properties for Young's modulus and Poisson's ratio are 202 GPa and 0.29 respectively. Two cylindrical blocks with a thickness 4 cm are used to hold and stand the pipe.

The pipe is connected to T-100K Kyowa test pump by a hose as shown in Figure 1. The hydro test pump will generate a pressure inside the pipe vessel by pumping the water from the water bath tank into the pipe. The pressure gauge positioned hydro test pump will provide an output pressure supply inside the tank.

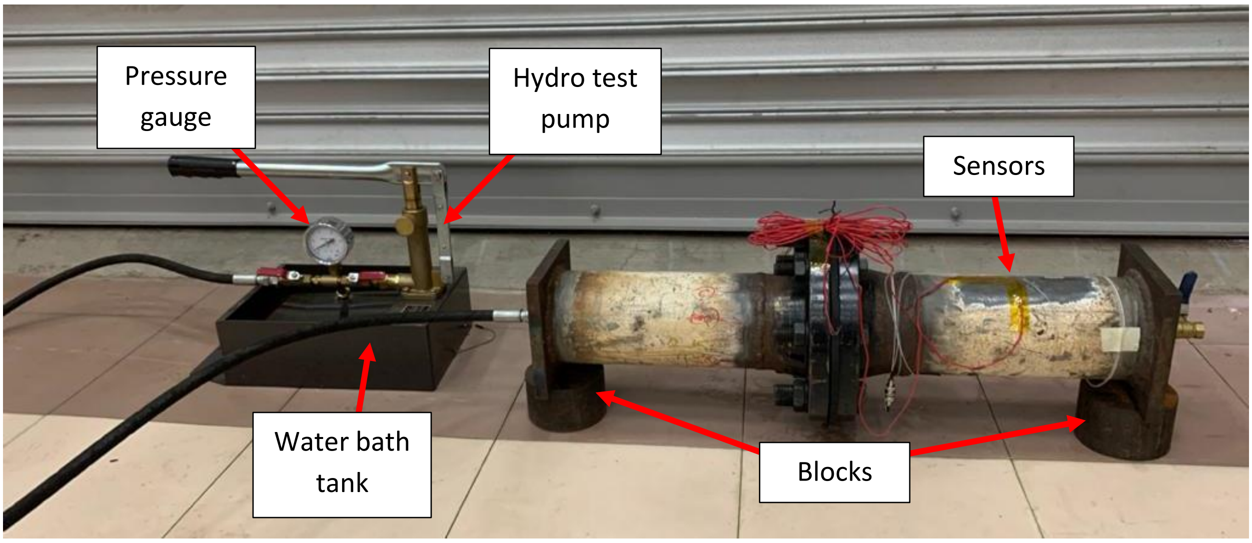


**Fig. 1.** Pipe and hydro test pump setup

### *2.2 Sensor and Interrogator*

The FBG sensor used is an acrylate coated single-mode (SM) fiber which made of silica glass, having a diameter of 10 µm and its clad diameter of 125 µm. The FBG sensor will measure the changes occur in the Bragg wavelength. Two FBG sensor with a wavelength of 1550 nm (FBG 1) and 1556 nm (FBG 2) were adopted by multiplexed these two sensors into a single line optical fiber to measure the longitudinal and circumferential strain respectively. These grating with a resonance wavelength range of 1550 nm were selected due to the higher strain sensitivity which approximately near 1.2 pm/µε [17]. The two selected FBG sensors must be different in Bragg wavelength in order to avoid any spectral overlap [18]. These sensors are bonded on the surface of the pipe in an orthogonal geometry on the principle axis of the pipeline by using cyanoacrylate glue as shown in Figure 2. The strain sensitivity of directly-adhered FBG sensor is 1.2 pm/με [19, 20]. Under a constant room temperature at 27.5 °C, the relationship between the changes of the central wavelength of the FBG ($\Delta\lambda_B$) and the strain can be expressed as follows [21, 22]

$$\Delta\lambda_B = \lambda_B(1 - p_e)\varepsilon \tag{4}$$

where $\lambda_B$ is the central wavelength, $P_e$ is the effective photo-elastic coefficient of the fiber with a fixed value of 0.22 for a germanium doped silica fiber and $\varepsilon$ is the strain acts on the optical fiber.

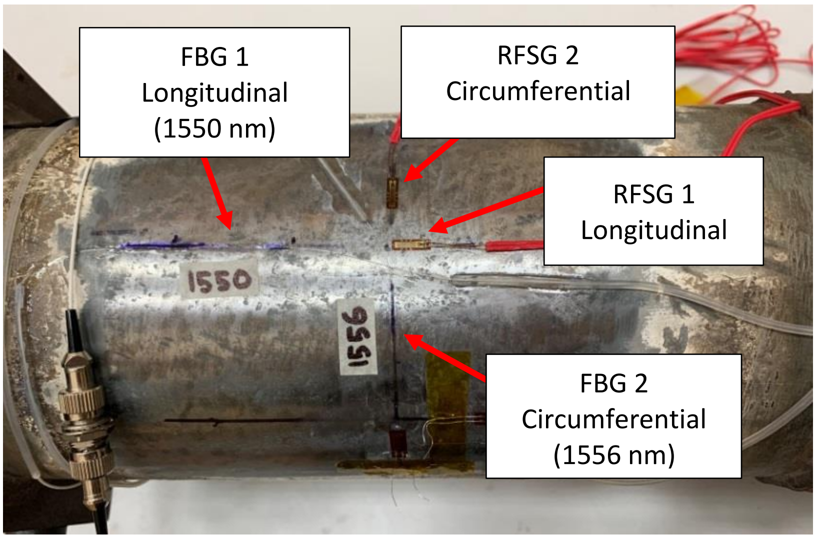


**Fig. 2.** FBG and RFSG sensors layout in an orthogonal position on the pipe's surface

A super-luminescent diode (SLD) light source manufactured by ThorLabs was used with an output power of 112.0 mA being set. The light source is connected to the FBG sensors by using a circulator. Figure 3 displays a schematic illustration of the sensor instrumentation. The back-reflected spectrum from the FBG sensor was captured by optical spectrum analyser (OSA) and monitored by using a computer or PC.

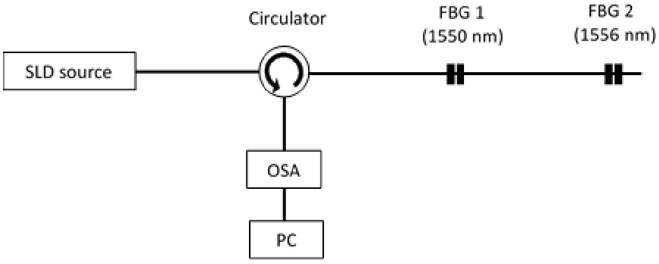


**Fig. 3.** Schematic illustration of the experimental layout for FBG demodulation instrument

The conventional RFSG sensors are used to compare the result data obtained by the FBG sensors. These sensors are mounted and glued to the pipe surface in adjacent with FBG sensor to measure the circumferential and longitudinal surface strain measurement (refer to Figure 2). The gauges are made of a metal with a resistance of 120. 4 Ω and gage factor of 2.08. The NI USB-9219 data acquisition system is applied to measure the strain variation. A DASYLab software is then used to communicate with the National Instrument (NI) hardware by using NI-DAQmx driver.

### *2.3 Test Procedure*

The distribution of surface strain induced in the seamless A53 carbon steel pipe was investigated by measuring a circumferential and longitudinal strain. The pipe was internally pressurized by using the tap water and performed under a series of pressure ranging from 0 to 5 MPa with a maintained temperature under control room temperature in 27.5 °C. The internal pressure is increases with a step of 1 MPa and maintained for at least 3 minutes in each step.

Under a constant temperature room of 27.5 °C, the initial central wavelength of FBG sensor is recorded at 1550.6432 nm (FBG 1) and 1556.4728 nm (FBG 2) as shown in Figure 4. The wavelength shift of FBG sensor is recorded from 1 to 3 minutes for each step to reach its stable condition. The test process is then repeated for three (3) times with loading and unloading step, in order to analyse the resilience and repeatability of both FBG and strain gauge sensors.

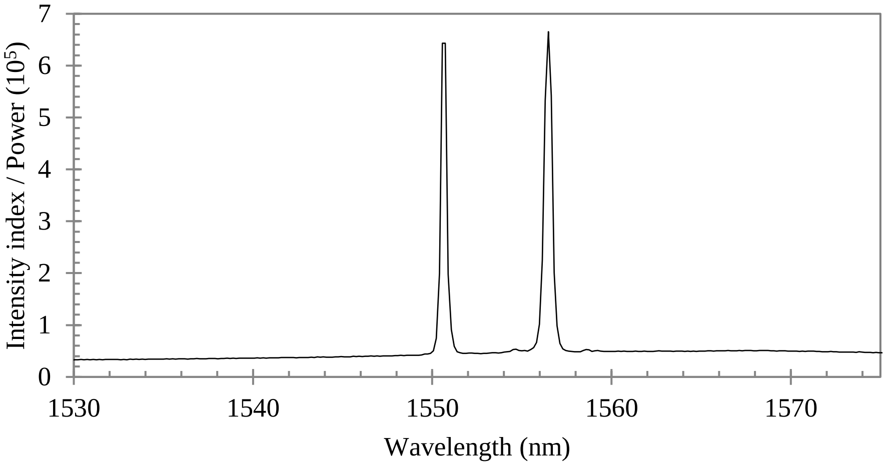
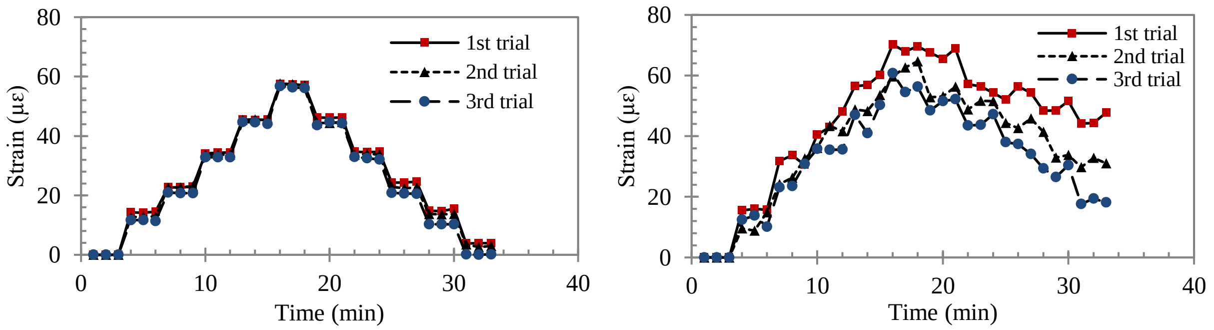


**Fig. 4.** Initial central wavelength spectrum of two multiplexed FBG sensor

## 3. Results and Discussion

The strain response in longitudinal direction was recorded at different pressure steps by pressurized the pipe to maximum of 5 MPa and then de-pressurized the pipe to its initial condition in order to validate the spectrum shape variation. The recorded data of longitudinal surface strain is plotted in Figure 5.

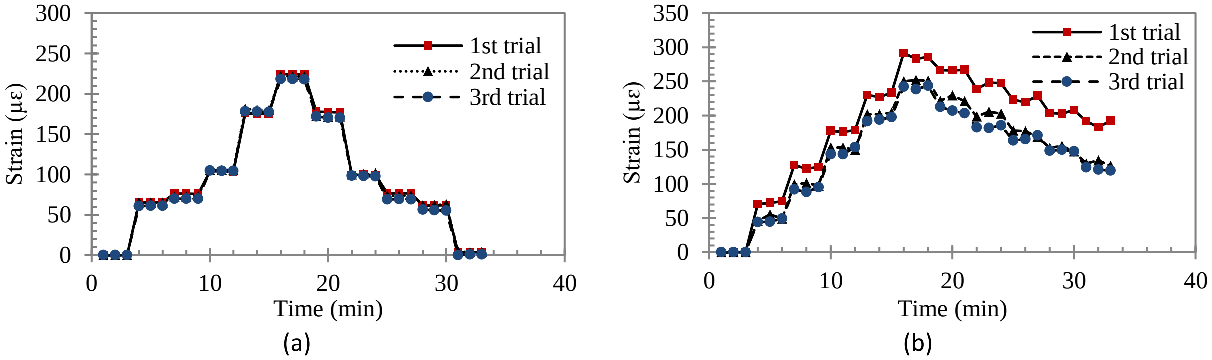


(a) (b)

**Fig. 5.** Plots of measured longitudinal strain during loading and unloading step using (a) FBG sensors (b) RFSG sensors

The longitudinal strain measurement data obtained as shown in above figure portrays a good reasonable agreement between both sensors. The strain response is initially proportional to the pressure. Throughout the test, it can be seen that the strain response of the FBG sensors does not vary and possess good stability and repeatability during loading and unloading period. The stability of the output signal is a main feature to validate the robustness of these sensors for SHM systems. It is important to achieve a repeatable data measurement for the precise strain output. However, the patterns of RFSG sensors are not truly consistent within the three replication trials and a hysteresis response is observed which is not detected by the FBG sensors. The RFSG sensors generate much noise compared to FBG sensors that significantly influenced the data precision of the RFSG sensors especially when the strains are relatively small.

Meanwhile, the strain response in circumferential direction was recorded and plotted in Figure 6 when the pressure is increased and decreased for loading and unloading period.



(a) (b)

**Fig. 6.** Plots of measured circumferential strain during loading and unloading step (a) FBG sensors and (b) RFSG sensors

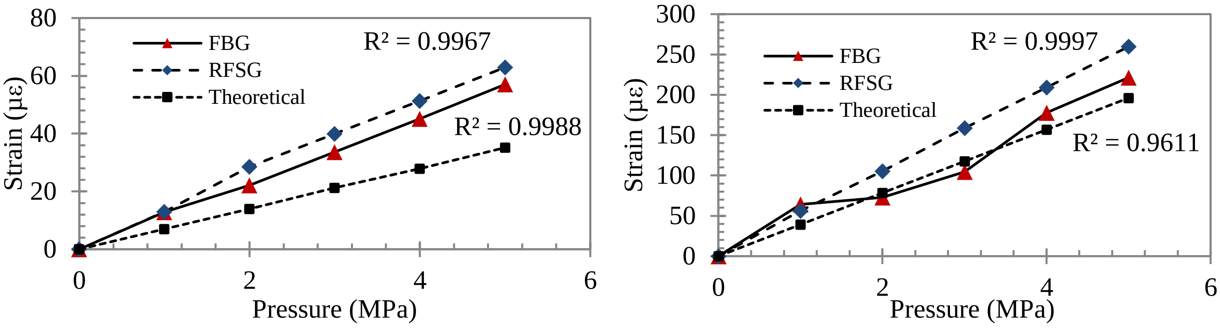
Similar with longitudinal strain, circumferential strain response is initially proportional to the applied pressure. In can be clearly seen that the circumferential strain possess a same trend pattern with a longitudinal strain which showing the FBG sensors possess higher repeatability and stability output compared to RFSG sensors. Comparing to Figure 5, the circumferential strain is much larger than longitudinal strain following the normal strain ratio 1:2 of longitudinal and circumferential direction of pipe under internal pressure [23]. The instrument repeatability error for both sensors were calculated and summarized in Table 1.

**Table 1**
Repeatability errors for both FBG and RFSG sensor

| Sensors | Sensor position | During loading condition (%) | During unloading condition (%) |
|---|---|---|---|
| FBG 1 | Longitudinal | 1.08 | 6.17 |
| FBG 2 | Circumferential | 0.75 | 2.08 |
| RFSG 1 | Longitudinal | 17.91 | 35.07 |
| RFSG 2 | Circumferential | 3.34 | 18.25 |

From an above Table 1, FBG sensors possess lower much lower repeatability errors with a percentage of 1.08% and 6.17% for longitudinal strain during loading and unloading period respectively. Meanwhile, for FBG circumferential strain, the percentages were recorded at 0.75% and 2.08% repeatability errors during loading and unloading condition. The lower repeatability errors indicated that the FBG sensors were constant in data measurements throughout the test. However, higher repeatability errors in longitudinal and circumferential strain value were recorded by RFSG sensors with a percentage error of 17.91% and 3.34% for loading condition and 35.07% and 18.25% for unloading condition respectively. Such discrepancy in data measurement could be suspected that RFSG sensors were suffering due to hysteresis error.

Next, the comparison of both surface strains was done by plotting the average value for longitudinal and circumferential strain versus pressure as can be seen in Figure 7. The Eq. (2) and Eq. (3) were used to provide a theoretical prediction of the strain values.



(a) (b)

**Fig. 7.** Average strain data versus pressure for (a) longitudinal strain and (b) circumferential strain

In this respective Figure 7, the errors in the data measurement are clearly noticeable between both sensors with a theoretical prediction. Based on Figure 7(a), FBG sensors had a higher linearity compared with RFSG sensors with $R^2$ = 0.9988. On Figure 7(b), the linearity of FBG sensors is $R^2$ = 0.9611 which much lower than RFSG sensors. It can be concluded that in term of linearity, FBG sensors exhibit an excellent linearity at the longitudinal strain measurements, with an accuracy error of only 0.12% for FBG sensors while 0.33% error for RFSG sensors. Meanwhile, RFSG sensors were much better for circumferential strain measurements with an accuracy error of 0.03% compared to FBG sensors with 3.89% error; however, the RFSG sensors suffer a systematic error. It clearly observed that the readings in both sensors were slightly above the theoretical value. These distinctions in readings might be due to a slight deviation in the angle alignment of the sensors and also the inconsistency in surface finishing or non-uniformity in the pipe thickness due to internal defects [24]. More tests are required to investigate its origin. However, since both FBG sensors patterns are much closer to the theoretical prediction values and possess higher stability output, it can be argued that FBG sensors are more accurate [15].

## 4. Conclusions

In this paper, a clear comparison between FBG and RFSG sensors has successfully presented by measuring the surface strain of a thick-walled pipe vessel subjected to internal pressure. It can be concluded that FBG sensors possess a better stability and repeatability data output with a lower percentage error ranging from 1.08% to 6.17% when compared to RFSG sensors with an error ranging from 3.34% to 35.07% in longitudinal and circumferential strain output respectively. In term of linearity, FBG sensors have the appearance of being more stable with a percentage error 0.12% in longitudinal strain and 3.89% in circumferential strain measurement. In the meantime, RFSG sensors recorded higher percentage error in longitudinal strain output with 0.33% error while in circumferential strain output; lower percentage error was recorded with only 0.03% error. However, these RFSG sensors suffer a systematic error due to hysteresis error. Therefore, it is clear that FBG sensors are more reliable in real-time monitoring and detecting the pressure variance in a pipeline.

**Acknowledgement**

The authors would like to thank the Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang (http://www.ump.edu.my/) for providing the laboratory facilities. The authors would also like to acknowledge the Institute of Postgraduate Studies (IPS), Universiti Malaysia Pahang for funding through the Master Research Scheme (MRS) scholarship. Finally, special thanks to the UMP Research and Innovation Department for providing the Postgraduate Research Grants Scheme (PGRS) under grant no. PGRS2003145; and internal research grant under grant no. RDU1903120.

## References

[1] Hamill, Marty, Franco Chakkalakal, and Jim Beres. "Building the World's Longest Heated Pipeline—A Technology Application Review." *IEEE Transactions on Industry Applications* 53, no. 1 (2016): 709-717. https://doi.org/10.1109/TIA.2016.2604778

[2] Zaki, Muhammad Mirza Mohd, Turki Al Qahtani, Noorfaizal Yidris, Shamsuddin Sulaiman, Ahmad Hamdan Ariffin, Mohd Saffuan Yaakob, and Kamarul Arifin Ahmad. "Design and Analysis of a Water Pipe Leakage Sensor." *CFD Letters* 12, no. 9 (2020): 51-59. https://doi.org/10.37934/cfdl.12.9.5159

[3] Efzan, MN Ervina, S. Kesahvanveraragu, and J. Emerson. "Microstructural Characterization and Hardness Properties of A333 Grade 6 Low Carbon Steel in Offshore Platform Pipelines." *system* 2, no. 11 (2014): 15.

[4] Yang, Zhao, Zhuang Xiong, and Min Shao. "A new method of leak location for the natural gas pipeline based on wavelet analysis." *Energy* 35, no. 9 (2010): 3814-3820. https://doi.org/10.1016/j.energy.2010.05.034

[5] Ren, Liang, Zi-guang Jia, Hong-nan Li, and Gangbing Song. "Design and experimental study on FBG hoop-strain sensor in pipeline monitoring." *Optical fiber technology* 20, no. 1 (2014): 15-23. https://doi.org/10.1016/j.yofte.2013.11.004

[6] Kumar, Ramesh, and Anurag Sharma. "A new method to analyze fiber Bragg gratings." *Optical Fiber Technology* 53 (2019): 102017. https://doi.org/10.1016/j.yofte.2019.102017

[7] Wang, Jian-Neng, and Jaw-Luen Tang. "Feasibility of fiber Bragg grating and long-period fiber grating sensors under different environmental conditions." *Sensors* 10, no. 11 (2010): 10105-10127. https://doi.org/10.3390/s101110105

[8] Haroon, Hazura, Abdul Aziz Abu Mansor, Hanim Abdul Razak, Siti Khadijah Idris, Anis Suhaila Mohd Zain, and Fauziyah Salehuddin. "Experimental performance analysis of macrobending loss characteristics in polymer optical fiber." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 14, no. 1 (2019): 1-7.

[9] Torres, Benjamin, Ignacio Payá-Zaforteza, Pedro A. Calderón, and Jose M. Adam. "Analysis of the strain transfer in a new FBG sensor for structural health monitoring." *Engineering Structures* 33, no. 2 (2011): 539-548. https://doi.org/10.1016/j.engstruct.2010.11.012

[10] Vorathin, E., Z. M. Hafizi, A. M. Aizzuddin, and Kok Sing Lim. "A highly sensitive multiplexed FBG pressure transducer based on natural rubber diaphragm and ultrathin aluminium sheet." *Optics & Laser Technology* 106 (2018): 177-181. https://doi.org/10.1016/j.optlastec.2018.04.003

[11] Tan, C. H., Y. G. Shee, B. K. Yap, and FR Mahamd Adikan. "Fiber Bragg grating based sensing system: Early corrosion detection for structural health monitoring." *Sensors and Actuators A: Physical* 246 (2016): 123-128. https://doi.org/10.1016/j.sna.2016.04.028

[12] Hafizi, Z. M., J. Epaarachchi, and K. T. Lau. "Impact location determination on thin laminated composite plates using an NIR-FBG sensor system." *Measurement* 61 (2015): 51-57. https://doi.org/10.1016/j.measurement.2014.08.040

[13] Timoshenko, S., and J. N. Goodier. "Theory of Elasticity" McGraw-Hill Book Company." *Inc. New York* (1951).

[14] Ghannad, M., M. Jabbari, and M. Nejad. "An elastic analysis for thick cylindrical pressure vessels with variable thickness." *Engineering Solid Mechanics* 3, no. 2 (2015): 117-130. https://doi.org/10.5267/j.esm.2015.1.003

[15] Groves, Roger M., Edmon Chehura, Weilai Li, Stephen E. Staines, Stephen W. James, and Ralph P. Tatam. "Surface strain measurement: a comparison of speckle shearing interferometry and optical fibre Bragg gratings with resistance foil strain gauges." *Measurement Science and Technology* 18, no. 5 (2007): 1175. https://doi.org/10.1088/0957-0233/18/5/003

[16] Ibrahim, Ahmed, Yeong Ryu, and Mir Saidpour. "Stress analysis of thin-walled pressure vessels." *Modern Mechanical Engineering* 5, no. 01 (2015): 1. https://doi.org/10.4236/mme.2015.51001

[17] Stefani, Alessio, Wu Yuan, Søren Andresen, and Ole Bang. "Polymer optical fiber Bragg grating sensors: Measuring acceleration." In *35th Australian Conference on Optical Fibre Technology*, pp. 1-4. IEEE, 2010. https://doi.org/10.1109/ACOFT.2010.5929947

[18] Manie, Yibeltal Chanie, Run-Kai Shiu, Peng-Chun Peng, Bao-Yi Guo, Mekuanint Agegnehu Bitew, Wei-Chieh Tang, and Hung-Kai Lu. "Intensity and wavelength division multiplexing FBG sensor system using a Raman amplifier and extreme learning machine." *Journal of Sensors* 2018 (2018). https://doi.org/10.1155/2018/7323149

[19] Li, Ruiya, Yiyang Chen, Yuegang Tan, Zude Zhou, Tianliang Li, and Jian Mao. "Sensitivity enhancement of FBG-based strain sensor." *Sensors* 18, no. 5 (2018): 1607. https://doi.org/10.3390/s18051607

[20] Liu, Mingyao, Wenzhi Wang, Han Song, Shiguang Zhou, and Weijian Zhou. "A high sensitivity FBG strain sensor based on flexible hinge." *Sensors* 19, no. 8 (2019): 1931. https://doi.org/10.3390/s19081931

[21] Liu, Hong-lin, Zheng-wei Zhu, Yong Zheng, Bang Liu, and Feng Xiao. "Experimental study on an FBG strain sensor." *Optical Fiber Technology* 40 (2018): 144-151. https://doi.org/10.1016/j.yofte.2017.09.003

[22] Vorathin, E., Z. M. Hafizi, N. Ismail, and M. Loman. "Review of high sensitivity fibre-optic pressure sensors for low pressure sensing." *Optics & Laser Technology* 121 (2020): 105841. https://doi.org/10.1016/j.optlastec.2019.105841

[23] Zhao, Jun-qing, Rong-guo Wang, Xiao-dong He, and Wen-bo Liu. "Strain monitoring of composite pressure vessel with thin metal liner using fiber Bragg grating." In *Second International Conference on Smart Materials and Nanotechnology in Engineering*, vol. 7493, p. 74930F. International Society for Optics and Photonics, 2009. https://doi.org/10.1117/12.840654

[24] Hendawy, Mostafa M. "The application of fibre optic instrumentation for HPHT pipeline bundle health monitoring." In *Offshore Technology Conference*. Offshore Technology Conference, 2017. https://doi.org/10.4043/27690-MS