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Real-time Local Buckling Monitoring in Oil/gas Pipelines Using Fiber Optic Sensors

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Abstract - The occurrence of local buckling, an external anomaly in pipelines, significantly contributes to pipeline incidents, posing challenges in monitoring such localized anomalies, particularly during pipeline operations. This paper introduces an approach aimed at monitoring local buckling occurring in the compression bending area of pipeline sections. The proposed approach utilizes fiber Bragg gratings (FBGs) to facilitate real-time measurement of strain changes. Experimental tests were conducted on the steel pipe equipped with FBGs positioned near the top and bottom of the pipe, subjected to four-point loading test to generate bending and local buckling. The strain data obtained from FBGs enable effective detection and localization of bending and buckling deformations during the loading process. This research contributes to enhancing the capability to monitor external threats to pipelines, thereby fostering improved condition assessments and bolstering infrastructure resilience.

***Keywords*:** Local buckling; fiber Bragg gratings (FBGs); condition monitoring; pipeline safety.

1. Introduction

Oil and gas transmission pipelines play a critical role in facilitating the transportation of these essential energy resources, thereby contributing significantly to the national economy [1]. However, many pipelines are susceptible to various anomalies, such as corrosion, buckling, and cracks, which pose potential threats to pipeline integrity, potentially leading to pipeline failures, human health hazards, and disruptions in oil and gas supplies [2]. Thus, there exists an urgent imperative to develop innovative techniques for the early detection and assessment of pipeline anomalies.

Pipeline defects can arise at various stages, including during manufacturing, construction, and operation processes. This study focuses on operational defects, particularly third-party damage, bending and local buckling. Research indicates that local buckling presents higher risks when located on the compression side of a pipeline [3]. This heightened risk is attributed to significant curvature alterations in the pipe wall within the deformed region, resulting in an abrupt change in angle. Therefore, monitoring local buckling in the compression position is crucial.

To address the detection of pipeline anomalies, numerous techniques have been developed, with particular emphasis on non-destructive and in-situ sensors. In recent years, optical fiber sensors have emerged as prominent tools for continuously monitoring structures due to their inherent advantages, including small size, high precision, immunity to electromagnetic interference, corrosion resistance [4], [5], [6]. Among optical fiber sensors, fiber Bragg gratings (FBGs) exhibit relevant characteristics for structural integrity monitoring. FBGs have been applied in various pipeline damage identification applications. For instant, Jiang et al. [7] developed an FBG strain loop sensor capable of simultaneously monitoring pipeline leakage and corrosion. Experimental results demonstrate the promising potential of FBG strain hoop sensors in pipeline safety monitoring. Similarly, Wang et al. [8] introduced an innovative FBG pipe-fixture sensor, yielding consistent results. Additionally, Paiva et al. [9] conducted fatigue tests on dented steel pipeline specimens subjected to cyclic internal pressure, deploying Fiber Optic Bragg Strain Gauges (FBSG) at potential locations. Test results confirmed the efficacy of FBSGs in predicting the fatigue life of dented pipeline specimens.

Despite these advancements, there remains a research gap concerning the application of FBGs for monitoring local buckling on the compression side of pipelines. Therefore, the primary objective of this study is to evaluate the performance of FBGs in monitoring bending-induced compression and local buckling occurring at the same position within a pipe. Then, sensor data processing and interpretation are performed to assess pipeline conditions. A laboratory test was conducted using a 2550 mm length pipe specimen instrumented with FBGs and subjected to four-point bending testing. The strain measurements obtained from FBGs were utilized for the detection, localization, and quantification the local buckling.

2. Fiber Bragg Grating Sensing

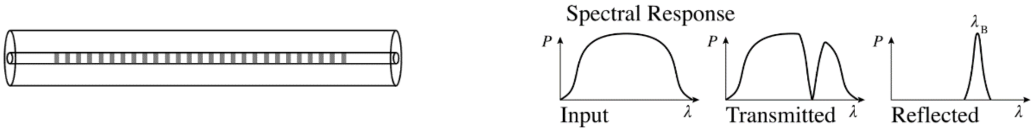
In an FBG sensor, fiber Bragg gratings are constructed by writing periodic variation in the refractive index into the core of an optical fiber using the UV laser, which reflects the particular wavelength, the Bragg wavelength λ_B, and transmits all others, as shown in Fig. *1* (a, b). Due to an applied strain $\Delta\varepsilon_{FBG}$ or a change in temperature ΔT, the shift in Bragg wavelength $\Delta\lambda$ can be given by [10]:

$$\Delta\lambda = \lambda_B[(1 - P_e)\Delta\varepsilon_{FBG} + (\alpha + \xi)\Delta T] \tag{1}$$

where P_e is the photo elastic coefficient of the fiber, α and ξ are the thermo expansion coefficient and the thermo-optic coefficient of the fiber, respectively. If the external temperature remains the same or can be compensated by a strain-free reference FBG sensor under the same working condition [11], Eq. (2) can be written as:

$$\Delta\lambda = \lambda_B(1 - P_e)\Delta\varepsilon_{FBG} \tag{2}$$

Thus, the external strain changes can be obtained from Eq. (2).



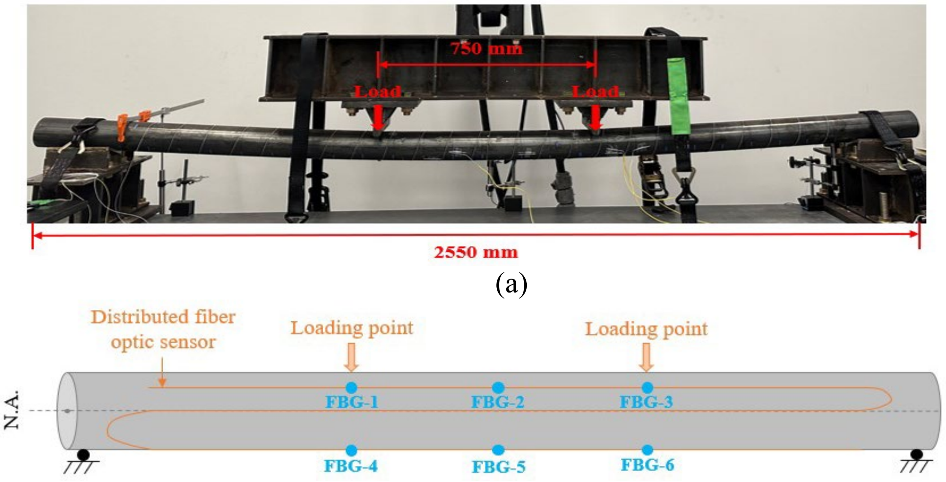
(a) (b)

Fig. 1 Schematic of fiber Bragg grating structure, (a) refractive index in a uniform FBG, and (b) spectral response.

3. Experimental Program

The 2550 mm-length pipe underwent loading under four-point bending to generate bending and local buckling deformations at the middle span, utilizing a load frame setup depicted in Fig. *2* (a). The pipe was supported by two rollers positioned 2550 mm apart, while the distance between the two loading points was 750 mm. The tests were conducted under displacement control at a constant rate of 1 mm/min. The applied loads were automatically measured and recorded by the load cell embedded within the load frame.

The deployment of FBG sensors is illustrated in Fig. *2* (b). A total of six FBG sensors were installed for monitoring. FBG-1 to FBG-3 were positioned near the top of the pipe, with FBG-1 and FBG-3 corresponding to the loading points, and FBG-2 affixed at the mid-point of the pipe. FBG-4 to FBG-6 were installed at the bottom of the pipe, mirroring the positions of FBG-1 to FBG-3, respectively.



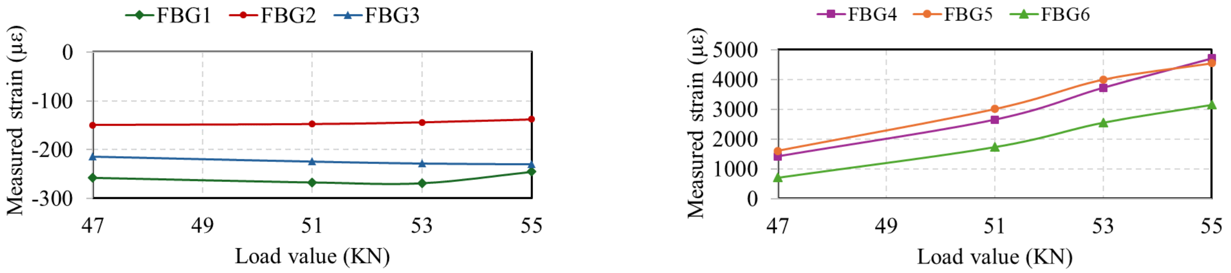
(a)

(b)

Fig. 2 Experimental test set-up: (a) photograph of the four-point bending test; (b) deployment of FBG sensors on the pipe-elevation view.

4. Results and Discussion

Fig. 3 illustrates the strain changes measured by FBGs in response to load-induced bending and local buckling, specifically focusing on the strain changes observed during load increments from 47 KN to 55 KN. FBG-1 to FBG-3, positioned near the top of the pipe, exhibited compressed strain changes during the four-point bending test; while FBG-4 to FBG-6, situated at the bottom, displayed tensile strain changes. As FBG-1 & FBG-3 and FBG4 & FBG-6 were symmetrically placed relative to the vertical centerline of the pipe, similar strain changes were expected under identical load levels. However, FBG-1 and FBG-4 exhibited notably larger strain changes compared to FBG-3 and FBG-4. This can be attributed to localized circumferential deflections, stress concentrations induced by localized loads, and slight pipe rotation during loading [12]. Although strain readings differed among FBGs, the overall trends remained consistent. In the tensile-stressed area at the bottom of the pipe, strain changes recorded by FBG-4, FBG-5, and FBG-6 increased with escalating external loads. Notably, FBG-5 at the midpoint showed the largest strain changes, corresponding to the most significant bending deformation along the bottom of the pipe. Regarding localized buckling detection and monitoring near the top of the pipe, FBG-1 and FBG-3 displayed more pronounced strain changes compared to FBG-2, indicating the occurrence of compressed bending and local buckling at the four-point loading positions.



(a) (b)

Fig. 3 Strain changes measured by FBG sensors corresponding to different load values.

5. Conclusions

This study proposes a method for detecting and monitoring local buckling within the compression bending area of pipeline using fiber Bragg grating sensors (FBGs). FBGs offer a means to monitor interactive bending and local buckling by measuring real-time strain changes induced by the external mechanical loads. The strain measurements enable the tracing and localization of both uniform and localized deformations. Specifically, FBG-4 to FBG-6 positioned along the bottom of the pipe effectively monitored the bending deformation, with their strain changes increasing alongside load increments. Meanwhile, FBG-1 and FBG-3 exhibited more pronounced compressed strain changes resulting from the interaction between bending and local buckling compared to FBG-2. The findings of this study underscore the effectiveness of FBGs in real-time detection and monitoring of bending and local buckling, providing valuable insights for pipeline structural health monitoring and maintenance practices. The ability to promptly identify and address external anomalies through FBG technology carries significant implications for enhancing pipeline transmission durability and longevity.

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