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Experimental and finite element analyses on the corrosion of underground pipelines

SUN Li[1*], CHEN Chen[1] & SUN QianQian[2]

[1] *School of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, China;*
[2] *Liaoning Urban Architectural Design Institute, Shenyang 110168, China*

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Underground pipelines, on which a city relies for survival and development, have become an important part of lifeline engineering. Underground pipelines are utilized for conveying liquid, gas or loose solid, pipeline leakage and damage occasionally resulting from corrosion. Corrosion monitoring of underground pipelines is aimed at ensuring their normal operation and preventing loss of life and property. In this paper, a new method to monitor corrosion of pipelines has been proposed to solve the mentioned problem. Under the influence of internal pressure and corrosion, the pipeline wall becomes thinner and the circumferential deformation increases. The method is to indirectly investigate pipeline corrosion by monitoring the circumferential deformation. Numerical simulation confirms that the circumferential strain curve of the pipeline wall measured by using the proposed method to describe the corrosion is feasible. The proposed method provides a new way for real-time and long-term monitoring and management of underground pipelines.

underground pipeline, fiber bragg grating sensor, corrosion monitoring

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1 Introduction

It is of great importance for enhancing operation efficiency of engineering structures and ensuring the security of people's life and property to real-time monitor and diagnose the performance of key engineering structures, to timely detect damaged parts of the structure and to evaluate its margin of safety and predict its remaining life [1]. Fiber Bragg grating (FBG) has been widely applied in structural health monitoring due to the advantages of simple structure, high sensitivity and accuracy, anti-electromagnetic interference, strong reliability, good stability, quasi-distributed measurement, easy network formability, real-time online monitoring, etc. [2].

It is well known that underground pipelines are under severe working conditions. The consequences are very serious once underground pipeline accident occurs [3]. Corrosion is one of the major contributors to underground pipeline accidents [4]. It is a time-pressing problem to effectively realize real-time health monitoring of the underground pipelines and timely recognize the cumulative damage [5]. In order to discriminate the health status of underground pipelines, it is necessary to detect the response signals under various loads by effective technical means. However, the observability of input signals is poor and the SNR (signal to noise ratio) is low because of the severe working conditions, so routine inspection and maintenance are difficult to carry out. Therefore, the research on health monitoring of underground pipelines is necessarily demanding and challenging. Many representative corrosion monitoring methods have been proposed, such as electrical

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*Corresponding author (email: sunli2009@163.com) resistance technique [6,7], which is sensitive to general corrosion but limited to localize corrosion, electrochemical impendence spectroscopy [8,9], which has been successfully applied to the study of corrosion systems, linear polarization resistance [10,11], which is proved to be a powerful tool for hot corrosion monitoring and galvanic sensor techniques, etc.

Each method has its own advantages and limitations. However, all of these methods are off-line detection methods and can hardly monitor corrosion of underground pipelines well since electricity is involved. In recent years, a new kind of light source device, FBG sensor, has become a hotspot in sensing research. Over the past few decades, fiber Bragg grating (FBG) sensors have emerged as a suitable, accurate and cost-effective tool in SHM [12]. High-speed internal strain measurements of composite structures under dynamic load can also be measured by FBG sensors [13]. Fiber Bragg Grating sensors are also proved to be effective in vibration control of smart structures [14]. FBG sensors are versatile with functions of normal sensors and the capability of measuring some special physical properties, such as temperature, pressure, strain, etc., opening up a new way to monitor and research the health status of underground pipelines [15]. With the implementation of FBG laser side writing technology, FBG manufacturing technology continues to be improved. More effort has been made to deeply study the optical sensing of FBG [16]. Therefore, the adoption of FBG sensors becomes an important tendency in the field of structural health monitoring [17].

Usually, corrosion of underground pipelines cannot be observed directly and the leaking location cannot be detected timely. To solve the problems, a new method to monitor the corrosion of underground pipelines has been proposed in this paper. In this method, packaged FBG sensors are attached to the outer wall of pipelines to monitor the circumferential strain of the outer wall in order to indirectly determine the corrosion status. This method is verified to be feasible by experiment and finite element analysis, and it is deserved to be applied and promoted. A countermeasure is provided for disaster prevention and mitigation of underground pipelines.

2 Principle of pipeline corrosion monitoring with FBG sensors

While in operation, oil, gas or some other substances are transported through pipelines by means of high pressure. The pipe will expand under such pressure, resulting in the circumferential deformation. The circumferential strain is given by

$$\varepsilon_y = \frac{\sigma_y - \upsilon\sigma_z}{E}, \tag{1}$$

where v is the Poisson's ratio σ_y and σ_z are circumferential stress and axial stress, respectively; E is the elastic modulus. Assuming that the pipeline is infinitely long, the axial strain of the pipe due to internal pressure can be negligible, that is σ_z=0. σ_y is given by

$$\sigma_y = \frac{PR}{h}, \tag{2}$$

where P is the pressure difference between internal and external pressure which can be regarded as substantially constant; R is the inner diameter of the pipe; and h is the thickness of the pipe. On the substitution of σ_y and σ_z in to eq. (1), the thickness of the pipe can be expressed as

$$h = \frac{PR}{\varepsilon_y E}. \tag{3}$$

As can be seen from eq. (3), with the reduction of the thickness of the pipe wall due to corrosion, the circumferential strain ε_y will increase. On the contrary, if the circumferential strain variation can be monitored, the variation of the thickness of the pipe wall can be determined, and then the corrosion status can be determined.

Temperature is an important parameter that needs to be taken into consideration in structural health monitoring. In order to eliminate the influence of temperature on strain measurement, it is necessary to use extra FBG temperature sensors in actual pipeline corrosion monitoring for the purpose of temperature compensation.

3 Finite element simulation and analysis

In the present finite element model, solid element, i.e. pipeline element C3D20, was employed. The pipe is divided into 6 sections with 6 different thicknesses, which simulate 6 different corrosion statuses. Material and geometry properties of the pipe are tabulated in Table 1. In this example, an analytical step is defined to carry out static calculation under the pressure difference between internal and external pressure in underground pipelines. According to the specific circumstances of the test, the boundary conditions at both ends of the model were set as fixed support.

Figure 1 presents that the stress contours of the pipe model under different pressure respectively. The same variation as those in the test results can be observed from these figures. At a location the stress variations are dependent on the pressure difference between internal and external pressure, as well as the thickness of pipeline. Strain variation is gradually reduced with the increase of thickness. It turns out that with the increase of the extent of corrosion, the thickness of the pipe wall is reduced and the stress at the defect location is increased. Thus, we can determine the corrosion status according to the monitored strain. The defect location may be determined according to the location of the sensor.

Table 1 Material and geometry properties

E (GPa)	μ	Inner diameter (mm)	Outer diameter (mm)
3.4	0.2	85	88 89 90 91 92 93

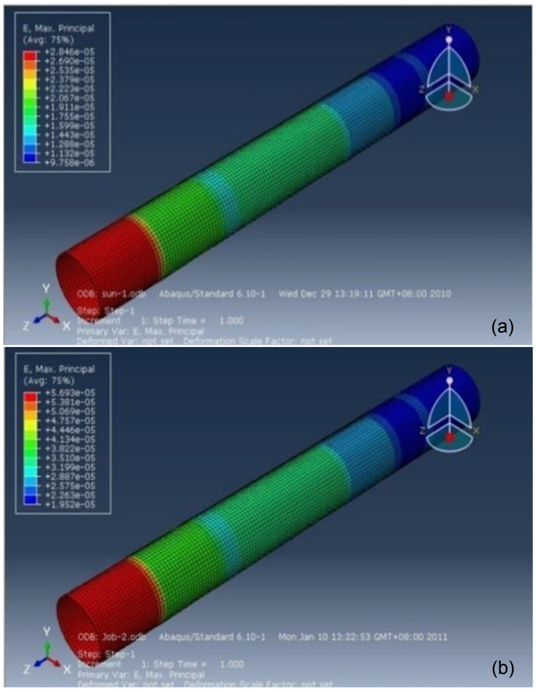

Figure 1 (Color online) Strain nephogram when (a) P_1=3430 Pa, (b) P_2=6860 Pa.

Thus, safeguard procedures can be taken as soon as possible. The strain changes due to corrosion are exactly shown quantitatively in curves in Figure 2.

4 Experimental study and analysis

Under the guidance of pipeline corrosion theory and finite element analysis, the experimental model and the detection method of FBG sensors were designed.

4.1 Model design

In the experimental model, organic glass (polypropylene resin) was used to simulate underground pipelines, because it possesses the characteristics of low elasticity modulus, high strength, fine texture and good machinability [18]. The elastic modulus of organic glass is taken as 3.4 GPa.

The pipes were made into sectional uniform models, as shown in Figure 3, with length L=1.5 m, the inner radius R=85 mm, and six thickness h=3 mm, h=4 mm, h=5 mm, h=6 mm, h=7 mm, h=8 mm. Different thickness is used to simulate different corrosion status. Five packaged FBG strain sensors, respectively numbered as 1#, 2#, 3#, 4#, 5#, were pasted at each section except that with thickness h=5 mm, where there is an outlet.

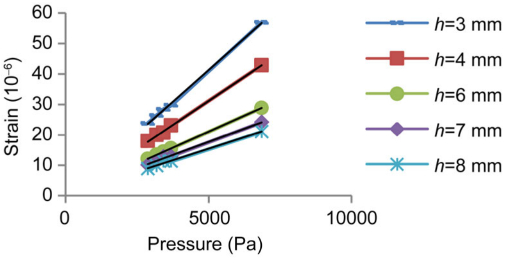

Figure 2 (Color online) P-ε drawing for different extent of corrosion.

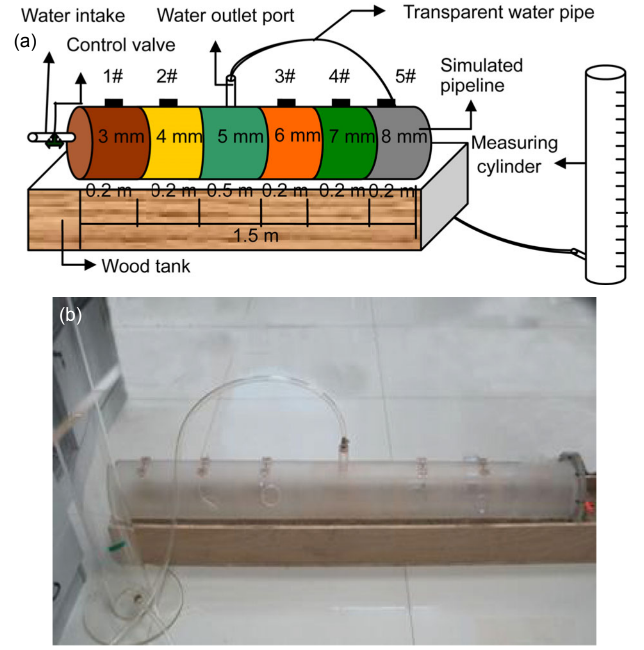

Figure 3 (Color online) (a) Diagrammatic of the pipeline model [19]; (b) sketch of the pipeline model.

A FBG temperature sensor was freely placed in the same temperature field near the pipeline to compensate the influence of temperature on strain. The sensors used in the experiment were tube steel packaged FBG strain sensor and the sensing structure of the sensor is shown in Figure 4. A universal testing machine is used to demarcate the packaged sensors. Then the strain sensitivity coefficients of the sensors were obtained and tabulated in Table 2.

Usually, the strain sensitivity coefficient of ordinary sensors is about 1.2 nm/με. But the data in Table 2 show that the strain sensitivity coefficients of the sensors demarcated in the experiment are larger than 1.2 nm/με, which verifies that the sensors achieved sensitizing effect and ensures more accurate monitoring result.

In order to prevent the pipelines from scrolling and ensure the loading of the pipe uniformly, the pipe was put straight in a wood slot covered with sand. These two factors

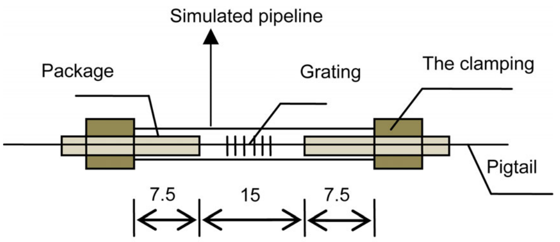

Figure 4 (Color online) The schematic diagram of FBG strain sensor with enhanced sensitivity.

Table 2 Strain sensitivity coefficients of sensors

Number	Wavelength (nm)	Strain sensitivity coefficient (nm/με)
1#	1547.500	2.7500
2#	1552.200	1.5415
3#	1563.641	1.3510
4#	1564.658	2.5000
5#	1532. 500	3.5000

will change the stress state of the sensors and affect the monitoring results. Then water was poured into the pipe through the inlet until the pipe is filled with water, keeping constant the surface of water connected with the measuring cylinder. The FBG sensors used in the experiment were clamped on the pipe wall using the same organic glass piece to keep the material properties consistent, avoiding the loss of strain transfer and ensuring more accurate monitoring results.

Finally, water was poured into the measuring cylinder and the liquid level was kept stable to a certain height. There was a corresponding pressure difference and the stress state of the pipe changed. Thus, the wavelengths of the sensors were changed because the sensors were pasted on the surface of the pipe. At the same time, the wavelengths, reflected back by the sensors at different locations with different thickness, also varies. During the entire experiment process, the variation of laboratory temperature is so small that it can be neglected.

4.2 Results and analysis

According to ref. [5], the relationship between the wavelength and the strain is given by $\Delta\lambda = \alpha_{\varepsilon}\varepsilon$. Therefore, variation of wavelength can be obtained through the corresponding variation of strain. The experiment results are presented in Tables 3 and 4 and Figure 4.

The comparison between experimental and theoretical data in Table 3 shows that the tested result is relatively close to the theoretical data even though the test was conducted indoors, ignoring the impact of environment and temperature.

Figure 5(a) presents the stress-strain diagram when the thickness of pipe wall h=4 mm. A phenomenon can be observed from the figure that different strain variation occurs at the location with the same thickness under different pressure and there is a good linear relationship between the

Table 3 Strain variation

	h (mm)	3	4	6	7	8
P_3=2881.2 Pa	Tested data ($\times10^{-6}$)	25.091	18.488	12.583	10.8	8.857
	Theoretical data ($\times10^{-6}$)	24.01	18.008	12.005	10.29	9.003
	Error (%)	4.502	2.665	4.815	4.956	1.622
P_4=3194.8 Pa	Tested data ($\times10^{-6}$)	27.273	20.049	13.323	11.6	10
	Theoretical data ($\times10^{-6}$)	26.623	19.967	13.312	11.41	9.984
	Error (%)	2.441	0.411	0.083	1.665	0.160
P_1=3430 Pa	Tested data ($\times10^{-6}$)	29.091	21.129	14.064	12.8	11.143
	Theoretical data ($\times10^{-6}$)	28.583	21.437	14.292	12.25	10.719
	Error (%)	1.777	1.437	1.595	4.490	3.956
P_5=3694.6 Pa	Tested data ($\times10^{-6}$)	30.909	24.431	14.804	13.6	11.714
	Theoretical data ($\times10^{-6}$)	30.224	23.091	15.394	13.195	11.545
	Error (%)	2.266	5.803	3.833	3.069	1.464
P_2=6860 Pa	Tested data ($\times10^{-6}$)	59.273	42.258	29.608	25.2	20.857
	Theoretical data ($\times10^{-6}$)	57.167	42.875	28.584	24.5	21.437
	Error (%)	3.684	1.439	3.582	2.857	2.706

Table 4 Error analysis of the test results

	P_1	P_2	P_3	P_4	P_5
Theoretical data deduced from the test (Pa)	3479.3	6942	2969.4	3225.2	3745.5
Theoretical data (Pa)	3430	6860	2881.2	3194.8	3694.6
Error (%)	1.44	1.20	3.06	0.95	1.38

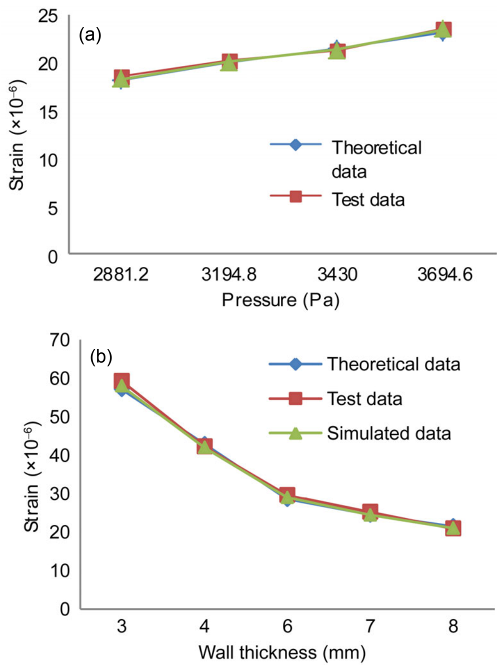

Figure 5 (Color online) (a) P-ε relationship when the wall thickness h=4 mm; (b) h-ε relationship when the pressure difference P=6860 Pa.

pressure and strain variation. Figure 5(b) presents the relationship between thickness and strain when the pressure difference P is 6860 Pa. When the pressure difference is constant, the strains at the locations with different thickness vary.

There is also a good linear relationship between thickness and strain. With the increase of thickness, strain variation gradually decreases, which is in good agreement with the theoretical result. The thickness will be reduced under corrosion, thus the extent of corrosion can be determined according to strain variation.

Table 4 presents a comparison between the pressure derived from the test data with the theoretical pressure, together with the error between the test and theoretical data. Therefore, it can be seen from the result that the FBG sensors are suitable for health monitoring of pipeline structures, and the proposed method can be used for real-time strain variation monitoring of the pipeline.

5 Conclusions

Through experiment and finite element analysis, the proposed new type of corrosion-resistant sensor turns out to possess characteristics of easily manufactured, reliable performance, nondestructive to structure and extended service life. Moreover, it is suitable for long-term monitoring of temperature and strain under severe conditions. The proposed method provides online real-time monitoring of strain variation of pipelines, so that the weak location of the pipelines can be discovered timely and remedial measures can be taken to reduce risk. The current numerical and experimental stains are ‘the uniform circumferential strain’ of pipe walls with different thickness while corrosion in pipe wall leads to ‘local non-uniform circumferential strain’. Therefore, it is necessary to further investigate numerical and experimental work on monitoring pipeline local circumferential strain due to corrosion.

Therefore, the safety of pipelines and overall economic efficiency can be improved. As a preliminary study, the paper just illustrates the feasibility of the pipeline corrosion monitoring method but does not conduct quantitative analysis, so the damage index of pipeline due to corrosion is not defined. Some important parameters effecting the corrosion, such as wall depth, different damage locations, as well as linkage should be taken into consideration in further research.

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