The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

The study of pipeline corrosion monitoring using fiber optic sensing technique

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ABSTRACT

Pipeline is an important structure for the transportation of oil and gas. However, pipeline corrosion threaten the security of pipeline operation seriously. Thus pipeline corrosion monitoring is one of the indispensable parts for the economical and safety operation. The direct phenomenon caused by corrosion is the reduction of the pipeline wall thickness. Based on the theory that the hoop strain is inversely proportional to the wall thickness of pipeline, therefore the reduction of the wall thickness can be reflected by the measured hoop strain directly. In this paper, a pipeline corrosion monitoring method using fiber Bragg grating (FBG) strain hoop sensor was presented. The bare FBG is encapsulated in such a way that the hoop strain of pipeline is transformed into an axial strain on fiber, thus the overall hoop strain variation caused by corrosion growth can be measured accurately. A PVC pipeline model and a steel pipeline model were made to simulate the pipeline with uniform corrosion. A series of experimental studies applying the FBG strain hoop sensors to detect corrosion were conducted on the PVC pipeline model and the steel pipeline model to verify its effectiveness and accuracy. Additionally, numerical analysis using ABAQUS software were also carried out to calibrate the test results. The results demonstrate that the hoop strain is inversely proportional to the wall thickness and the FBG strain hoop sensor is sensitive to the hoop strain variation, which means the uniform corrosion level can be detected exactly. The numerical analytical results verify the correctness of the test results. It can be concluded that the FBG strain hoop sensor has good performance in the pipeline corrosion measurement. The FBG strain hoop sensor is considered to be a promising device in pipeline corrosion monitoring.

Keywords: pipeline, FBG hoop-strain sensor, corrosion detection, hoop strain

1. INTRODUCTION

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Pipeline leakage has become a serious problem in long pipeline monitoring(Bouazza 2008;Zou 2010). Pipeline leakage accidents are caused by a variety of unexpected natural or man-made factors in which the corrosion is the main natural factor(Tennyson 2006).Although a lot of measures have been carried out to protect pipeline from corrosion，but it is hard to prevent the growth of pipeline corrosion. Thus pipeline corrosion monitoring is becoming an important work to decrease the threaten to the pipeline safety operation. Monitoring techniques for pipeline, such as the magnetic flux leakage method and the ultrasonic method(Raad 1987), mainly measure the variation of the wall thickness induced by corrosion. Both of these methods have advantages of easy operation and high precision and limitations such as munity to electromagnetic interference.

Gas and oil pipelines have many potential dangers which make electrical sensors inappropriate to use(Senior 1985). The fiber optic sensors (FOS) play a more and more important role in the field of pipeline inspection, owing to the advantages of geometric versatility, immunity to electromagnetic interference, multi-parameters measurements (strain, temperature, rotation, etc.), and fitting for measurement in harsh environment (Senior 1985)(Black 1993). Considering its superior abilities, this technique has been widely used into pipeline non-destructive evaluation (NDE)(Sonyok 2008). The fiber bragg grating (FBG)(Li 2009;Ren 2009; Ren 2007;Ren 2006; Hou 2013; Suresh 2004) is one of the typical quasi-distributed FOS, which can measure strain in many areas. Thus, its importance reflects not only in monitoring local strain, but also multi-point measurement which makes intelligent detection achievable.

According to the survey conducted by Wang Guili(Wang 2012), the most direct phenomenon caused by corrosions is the reduction of the wall thickness of pipeline, and in some way the hoop strain variation can reflect the change of wall thickness directly. Uniform corrosion is a kind of common corrosion morphology and measured by average corrosion depth(Wang 2008). In this paper, a new method to monitor uniform corrosion by the hoop strain measurement based on the FBG hoop-strain sensor is proposed. The uniform corrosion monitoring simulation and the characteristics of FBG hoop-strain sensor are investigated by conducting test, discussing results, figuring out parametric study of the sensor. Analysis were carried out in ABAQUS to verify the effectiveness of the monitoring theory and the veracity of the test. Results show that the FBG hoop-strain sensor, which is sensitive to the hoop strain variation, is a promising monitoring device with the advantages of accuracy, stability and reliability.

2. ANALYTICAL MODEL AND PARAMETRIC STUDY

2.1 Corrosion estimation based on hoop strain

The basic formula, which explains the relationship between the hoop strain and the wall thickness of the pipeline, is given directly:

$$\varepsilon = Pd/2Et \tag{1}$$

where ε is the hoop strain of the pipeline; *P* is the applied pressure; *E* is the Young's modulus and *t* is the wall thickness of the pipeline. It is assumed that *P* and *d* are the constants because pipelines usually work in the condition of steady pressure and the radius of the pipeline is a constant in the practical engineering project. Therefore, the hoop strain is inversely proportional to the wall thickness of pipeline, thus the change of the wall thickness can be reflected by the measured hoop strain directly. Based on this theory, the degree of the uniform corrosion can be measured by the monitoring result of the hoop strain. A hoop strain device is attempted to design, which can be attached on the external surface of pipeline and reflect the overall circumferential deformation on the same cross-section.

2.2 FBG HOOP-STRAIN SENSOR DESIGN

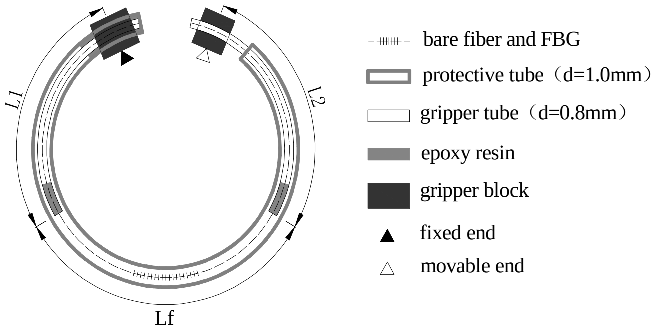

Fig .1 Schematic diagram of an FBG hoop-strain sensor

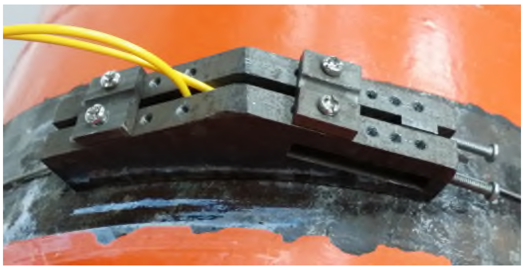

Fig. 2 The picture of the sensor clamp

Fig.1 shows the schematic diagram of the FBG hoop-strain sensor. This sensor consists of a FBG, two gripper tubes, two gripper blocks, a protective tube, a movable end and a fixed end. The fiber in both sides of FBG is packaged with the epoxy resin in the two gripper tubes. The protective tube is closely mounted onto the external surface of pipeline to be monitored. The fixed end and the movable end are both installed in the sensor clamp which is shown in Fig.2. The relationship between the hoop strain of the pipeline and the strain of FBG hoop-strain sensor εf can be expressed as:

$$\varepsilon_f = K\varepsilon \quad (2)$$

Where K is named as the FBG hoop-strain sensor strain sensitivity coefficient. For the FBG hoop-strain sensor used in these tests, the sensitivity coefficient *K* is 1.1. Substituting the relation of wavelength shift $\Delta\lambda_{FBG}$ and elongation of the fiber, i.e. $\varepsilon_f = \Delta\lambda_{FBG}/1.2$, into Eq. (2), the relationship among applied pressure, thickness and wavelength shift is given by:

$$\Delta\lambda_{FBG} = \gamma \frac{1}{t} \quad (3)$$

Where γ is given as $\gamma = 1.2KdP/2E$. For the PVC pipeline model and the steel pipeline model in this paper, the coefficients are γ_P = 1982.75 and γ_S = 167.71 respectively. The relationship among the wavelength shift and the thickness are obtained, that is the wavelength shift decrease as thickness increase.

3. TEST VERIFICATION OF THE PARAMETRIC STUDY

3.1 test set-up

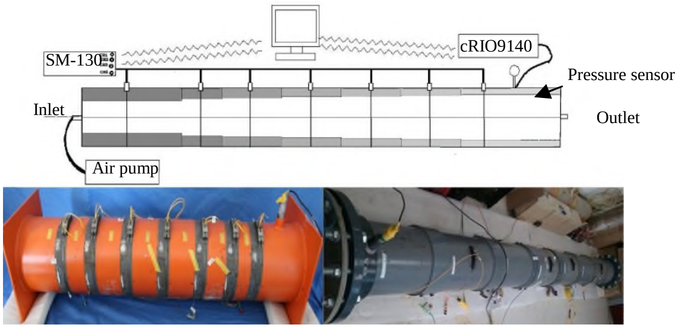

Fig. 3 The device physical figure of simulating different corrosion degrees

The schematic of the test set-up is shown in Fig. 3.The tests contained two model pipelines: one model is PVC pipeline model with 250mm diameter which consists of seven parts with the same length of 300mm and the different wall thicknesses (e.g. 7.8.mm, 6.0mm, 5.1mm, 4.4mm, 4.2mm, 3.8mm and 3.4mm); the other one is a steel pipeline model with 273mm diameter composed of seven parts with the same length of 150mm and the different wall thicknesses (e.g. 6.0mm, 5.0mm, 4.6mm, 4.2mm, 3.8mm, 3.4mm, 3.0mm). The different wall thicknesses of the pipeline models represent different uniform corrosion degrees. The FBG hoop-strain sensors, mounted on the surface of pipeline models by the super glue, were in the middle area of the seven parts of the PVC and the steel pipeline models respectively to avoid the influence of boundary condition. The sensors were connected to an interrogator (Micron Optics sm130). An air pump was set up to provide pressurized condition to pipeline models. The pressure sensors was installed on the pipeline models to measure the internal pressure. Since the FBG was sensitive to temperature as well, the test results measured by the FBG hoop-strain sensors were compensated by using a temperature sensor(Suresh 2004).

3.2 Corrosion monitoring simulation

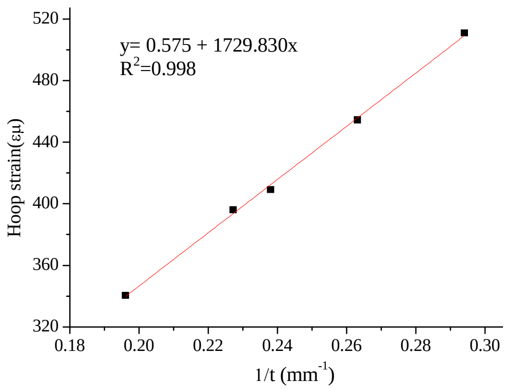

Fig. 4 PVC pipeline

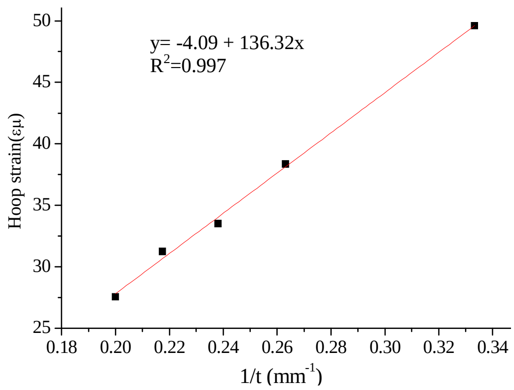

Fig. 5 steel pipeline

Based on the theoretical analysis that the hoop strain is in inverse proportion to the wall thickness of pipeline, corrosion monitoring simulation tests were conducted to verify the view that responses measured by the FBG hoop-strain sensors can reflect the corrosion degrees directly. In these tests, the PVC pipeline model with wall thicknesses 5.1mm, 4.4mm, 4.2mm, 3.8mm and 3.4mm and the steel pipeline model with 5mm, 4.6mm, 4.2mm, 3.8mm and 3.0mm were tested. The PVC pipeline model was pressured 50Kpa, while the steel pipeline model was pressured 200Kpa .

The regression coefficients of the linear variations of the FBG hoop-strain sensors are more than 0.99, which demonstrates that the packaging mechanism of sensor have no adverse effect to the hoop strain measurement and establishes linear equation between the hoop strain and the wall thickness of the pipeline model. The hoop strains measured by the FBG hoop-strain sensors give the sensitivity 1972.830pm/mm-1 and 136.32pm/mm-1 for the PVC pipeline model and the steel pipeline model (see Fig. 4 and Fig. 5), proving that the FBG hoop-strain sensors are sensitive to the hoop strain variations caused by corrosion. Therefore, considering the good performance of the FBG hoop-strain sensor on the pipeline models and the test results, the hoop strain measured by the FBG hoop-strain sensor can reflect the corrosion degree accurately. In addition, nondestructive condition monitoring and real-time monitoring are realized.

4. NUMERICAL ANALYSIS BASED ON FINITE ELEMENT METHOD

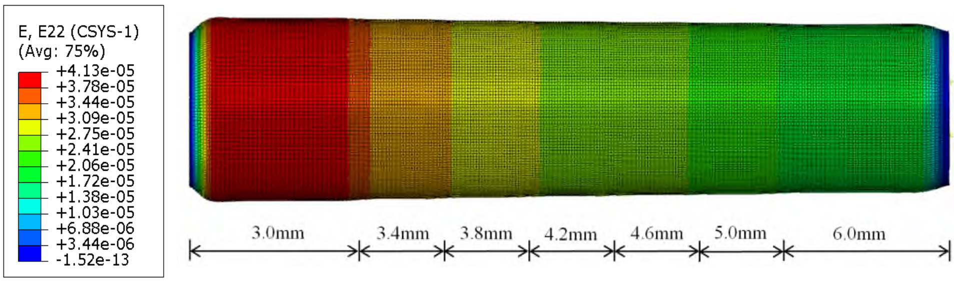

Fig. 6 The deformation Nephogram generated by ABAQUS

In order to demonstrate the relationship between the hoop strain variation and the corrosion condition and verify the reliability of the corrosion simulation test, the numerical simulation experiment was conducted on the steel pipeline model by the ABAQUS software under the applied pressure 200Kpa.The deformation nephogram is shown in Fig. 6. As shown in Fig. 7, the numerical analytical result shows a linear variation of the hoop strain with a regression coefficient over 0.9999, which demonstrates that the hoop strain is in inverse proportion to the wall thickness of pipeline strictly. Considering the numerical analytical results, the theoretical analytical results and the test results displayed in Fig. 7, all the results demonstrate that the pipeline wall extends uniformly and the circumferential deformations of pipeline decrease according to the rise of the wall thicknesses.

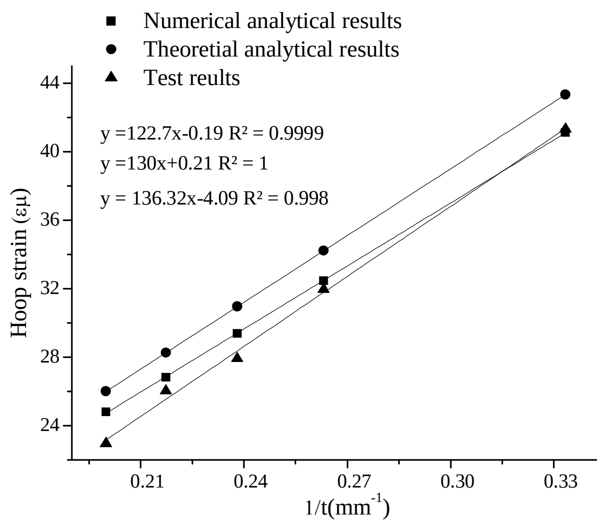

Fig. 7 Hoop strain measured by different methods

5. CONCLUSION

The principle of corrosion monitoring by using the FBG hoop-strain sensor was detailed. For investigating the characteristics of this sensor and verifying the feasibility of corrosion monitoring based on this method, the corrosion simulating tests were conducted. The results demonstrate that the FBG hoop-strain sensor is sensitive to the hoop strain variation and the hoop strain is in inverse proportion to the corrosion degree, which means corrosion condition can be detected exactly. The numerical analytical results verify the correctness of the test and provide the evidences to demonstrate that the constrain effect at variable cross-section are small enough to be neglected. Further study needs to be carried out, such as establishing of smart net-work. The FBG hoop-stain sensor is a kind of promising sensitive technique, has a broader prospect for development.

ACKNOWLEDGEMENTS

This work has been supported by the 973 Program (Grant No. 2015CB060000), the Fund of the National Natural Science Foundation of China (Grant No. 51421064 and 51327003), and the Fundamental Research Funds for the Central Universities (DUT15YQ107). These grants are greatly appreciated.

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