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Laboratory Evaluation of Dynamic Load Response of Coaxial Cable Fabry-Perot Interferometer Strain Sensors for Carbon Sequestration Monitoring

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ABSTRACT

Either surface transportation line integrity monitoring or downhole injection well tubular and rock formation integrity monitoring plays a crucial part in a geological carbon dioxide (CO_2) sequestration project, especially in providing early warnings of failure. Various monitoring technologies have been tested and applied in carbon sequestration projects world widely, whereas a lot of them are often low in spatial resolution and time-consuming, or expensive and have system longevity issues. The recent developed coaxial cable Fabry-Perot interferometer sensors have been put forward as a robust and cost-effective solution to carbon sequestration project monitoring strategies.

Flexible RG58 coaxial cable is used in the fabrication of Fabry-Perot interferometer strain sensors. The strain sensors were loaded with progressive dynamic loads with the tensile testing machine in laboratory and the sensor measurement results were compared with the electronic extensometer. The sensor characteristics such as measuring range and dynamic response accuracy were analyzed for changing reflection point distance during manufacture, loading speed of the tensile testing machine, and pretensions applied to the sensor before testing.

The results show that the coaxial cable Fabry-Perot interferometer strain sensors have steady performance under changing parameters as mentioned above, which means that the sensor accuracy remains invariable. The sensors have engineeringly accepted accuracy and almost real-time response to the dynamic loads applied during the test. And the sensors have large measuring range (up to 10,000 με) due to its excellent ductility. The research proves that the coaxial cable Fabry-Perot interferometer strain sensors can be as a feasible solution to carbon sequestration project monitoring strategies, and is of great value in providing early warnings of failure.

Keywords: Carbon sequestration, downhole monitoring, coaxial cable strain sensor, Fabry-Perot interferometer, dynamic load response

NONMENCLATURE

Abbreviations	
CCFPI	Coaxial Cable Fabry-Perot Interferometer
CO_2	Carbon Dioxide
EE	Electronic Extensometer
EM	Electromagnetic
FFPI	Fiber Fabry-Perot Interferometer
PE	Proportional Error
TTM	Tensile Testing Machine
VNA	Vector Network Analyzer
Symbols	
L	Sensor Reflection Point Distance
P	Pretension Applied on Sensor
V	Loading Rate of Tensile Testing Machine

1. INTRODUCTION

The safety regulations of CO_2 geological storage projects require that leakage must not exceed 0.01% per year, and it must be ensured that large-scale CO_2 leakage and escape does not occur after 100 years of injection[1, 2]. However, the inaccessibility and complexity of the

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potential storage formation and the sealing formations in the subsurface, the wide range of scales of variability, and the coupled nonlinear processes, impose tremendous challenges to determine the transport and predict the fate of the stored CO_2[3-6]. Comprehensive models of fluid flow in porous media are used to simulate the storage capacity and optimized injection of CO_2 into a storage formation, and coupled geomechanical and reservoir models is used to ensure safe storage[7-11]. However, the validation of such models is very challenging due to the limited understanding and limited data available for characterization of the subsurface temporal and spatial state variables and geologic media properties. Consequently, predictions based on current methodology are far too uncertain to achieve the goal to account for 99% of the injected CO_2[12, 13].

It is understood that no single data type alone is sufficient by itself to describe the complex underground characteristics and predict the fate of injected CO_2, and these data include geologic data, geophysical data, hydrologic data, geochemical data, and geomechanical data. Therefore, it is very necessary to use combined monitoring and description methods to monitor the entire injection process and the mitigation of the CO_2 injected into deep stratigraphic structures over a long period of time[14-16]. Among various monitoring methods, in situ downhole monitoring of state parameters (such as pressure, temperature, etc.) provides the most critical and direct data points that can be used to validate models, optimize injection schemes, detect leaks, and track CO_2 plumes[17-20]. However, groundbreaking research progress has yet to be made on sensors that can withstand harsh downhole conditions and operate for decades throughout the life cycle of the project. Given that the wide spread of CCUS projects will be the necessity and reality in the future, fundamental and applied research is required to address the significant challenges and technological gaps in developing reliable long-term sensors that can operate in downhole environments.

Coaxial cable sensor is a type of sensor based on electric time domain reflection technology and research in this area has made great strides in the past 20 years[21-23]. Currently, coaxial cable temperature sensors, strain sensors, pressure sensors, torque sensors, and magnetic field sensors have been successfully developed in laboratory. The electromagnetic shielding effect of coaxial cables is good, and the tensile strength is high. And one major advantage of coaxial cable is its low cost compared to other sensing materials such as optical fibers. When exposed to external substances such as water or when they are interrupted, stretched, twisted, etc., the characteristic impedance changes. This characteristic makes it possible for state parameter monitoring of coaxial cables. Since the 80s of the last century, coaxial cables have evolved from qualitative sensing elements based on parameters such as structural deformation (such as rocks and slopes) and cracks based on electric time-domain reflection technology to quantitative measurement sensors based on mechanisms such as the Bragg grating and Fabry-Perot interferometer.

Research has been conducted previously by the author on the characteristics of coaxial cable temperature and strain sensors in laboratory[24-26], however, in these tests, the sensors were tested under static conditions, which means the environmental temperature or applied strain were hold steady for a relatively long period. In this research, the characteristics of coaxial cable strain sensors are further studied under dynamic loading conditions in order to provide more proof that this type of sensor has the capability of providing downhole strain information in geological carbon sequestration projects.

2. TEST APPROACH AND EXPERIMENTAL SETUP

2.1 Working Mechanism of Coaxial Cable Fabry-Perot Interferometer (CCFPI) Strain Sensor

The design and working mechanism of CCFPI strain sensor is illustrated by Fig. 1. As indicated in this figure, two reflectors, separated at a distance of *L*, were implanted into the coaxial cable by inserting two small metal rods into the cable. The electromagnetic (EM) wave propagating inside the coaxial cable was partially reflected by these two implanted reflectors. The superposition of these two reflections produced an interference pattern in exactly the same way as in the case of a fiber Fabry-Perot interferometer (FFPI). When interrogated using a vector network analyzer (VNA), the CCFPI produces transmission and reflection spectra, respectively. The spectra are clean and show an excellent signal-to-noise. The strain induced cavity length and material property changes will produce a frequency shift in the interference pattern, which makes a CCFPI useful for strain sensing.

For more detailed explanation of the sensor working mechanism, please refer to the author's previously published articles mentioned above.

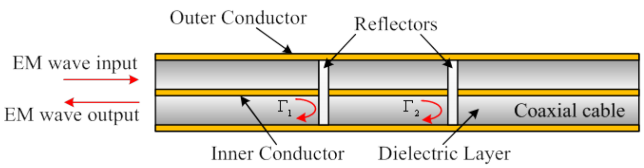

Fig. 1. Design of CCFPI strain sensor

2.2 Sensor Fabrication and Experimental Setup

The CCFPI strain sensor is made by compressing two copper crimp rings firmly onto the cable as the structural reflectors, as shown in Fig. 2. The coaxial cable used is type RG58. A pair of this kind of structural reflectors form one strain sensor.


Fig. 2. CCFPI strain sensor made in laboratory

The strain sensors are then loaded with progressive dynamic loads with the tensile testing machine in laboratory (Fig. 3) and the sensor measurement results are compared with the electronic extensometer. The prepared coaxial cable strain sensor is clamped to the tensile testing machine through a specific clip. One end of the coaxial cable is connected to the VNA, and the other end of the cable is connected to a terminator. The VNA used here is FieldFox Handheld Radio Frequency Vector Network Analyzer with 6 GHz peak power pulse

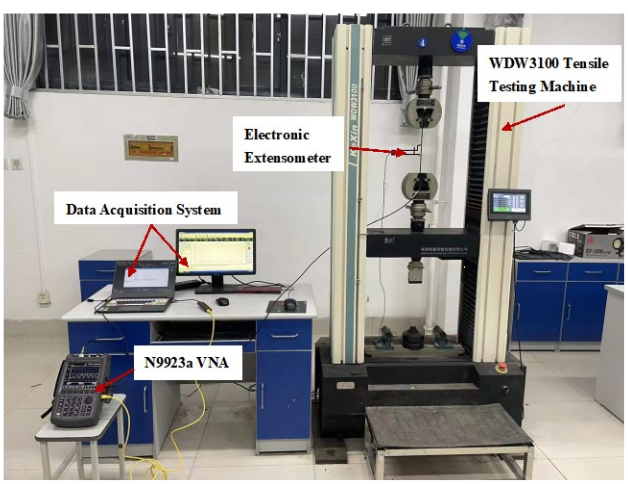

Fig. 3. Experimental setup

measurement. The tensile testing machine is controlled by a computer. Pretension is applied before the test to tighten the cable, and progressive dynamic load is applied on the sensor until the coaxial cable fracture. During the test the interference spectrum data is acquired by the VNA and the data is stored every 2 seconds, which is then transferred into strain measurement to compare with the electronic extensometer which is clamped tightly onto the coaxial cable strain sensor.

2.3 Test Scheme

The sensor characteristics such as measuring range and dynamic response accuracy are analyzed for changing reflection point distance during manufacture, loading rate of the tensile testing machine, and pretensions applied to the sensor before testing. Table 1 shows the test scheme, and each test was conducted twice under the same settings to cancel out any unexpected factors.

Table 1. Test scheme of CCFPI Strain Sensor Characteristics under Dynamic Loading

Test No.	Reflection point distance *L* (cm)	Pretension *P* (N)	Loading rate *V* (mm/s)
L-1	10	100	0.1
L-2	11		
L-3	12		
S-1	11	70	
S-2	11	100	
S-3	11	130	
V-1	11	100	0.02
V-2	11	100	0.05
V-3	11	100	0.1
V-4	11	100	0.12

3. RESULTS

3.1 Effect of Pretension

The nature that the sensor is made of a flexible material such as coaxial cable makes it almost impossible to keep it straight in a natural state, so it is necessary to apply pre-tensioning force to straighten it before the test. However, the amount of force that needs to be applied affects the mechanical performance during the tensile process, and will further affect the sensor performance, so it is essential to evaluate the influence of pretension on the performance of coaxial cable strain sensor.

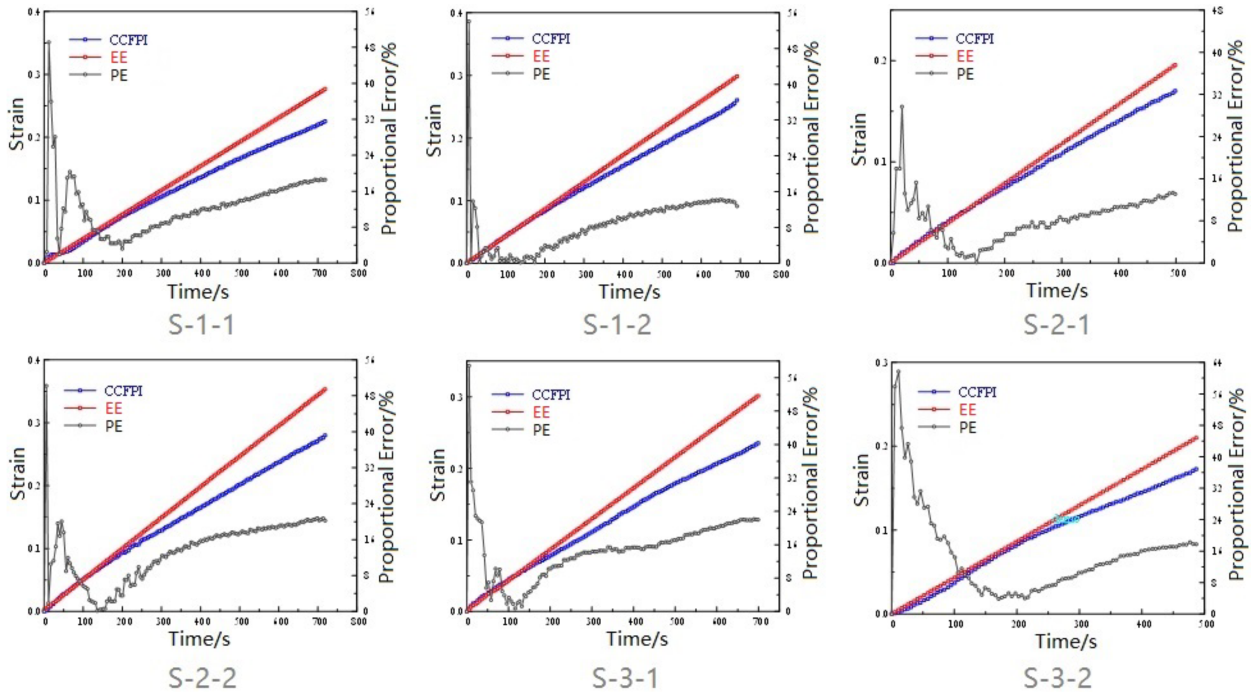

Fig. 4. CCFPI strain sensor vs. EE under different pretensions

Fig. 4 gives the strain-time relation during the test and proportional error curve for the CCFPI strain sensors under different pretensions. The strain measured by the sensor (in blue) at the beginning of the test was basically consistent with the strain measured by the electronic extensometer (in red). Due to the fluctuations of the load at the onset of the tensile testing machine, there was a large proportional error in the strain detected by the two, but the absolute error was very small. As the test progressed, the strain measured by the sensor was significantly smaller than the strain measured by the electronic extensometer, and the proportional error

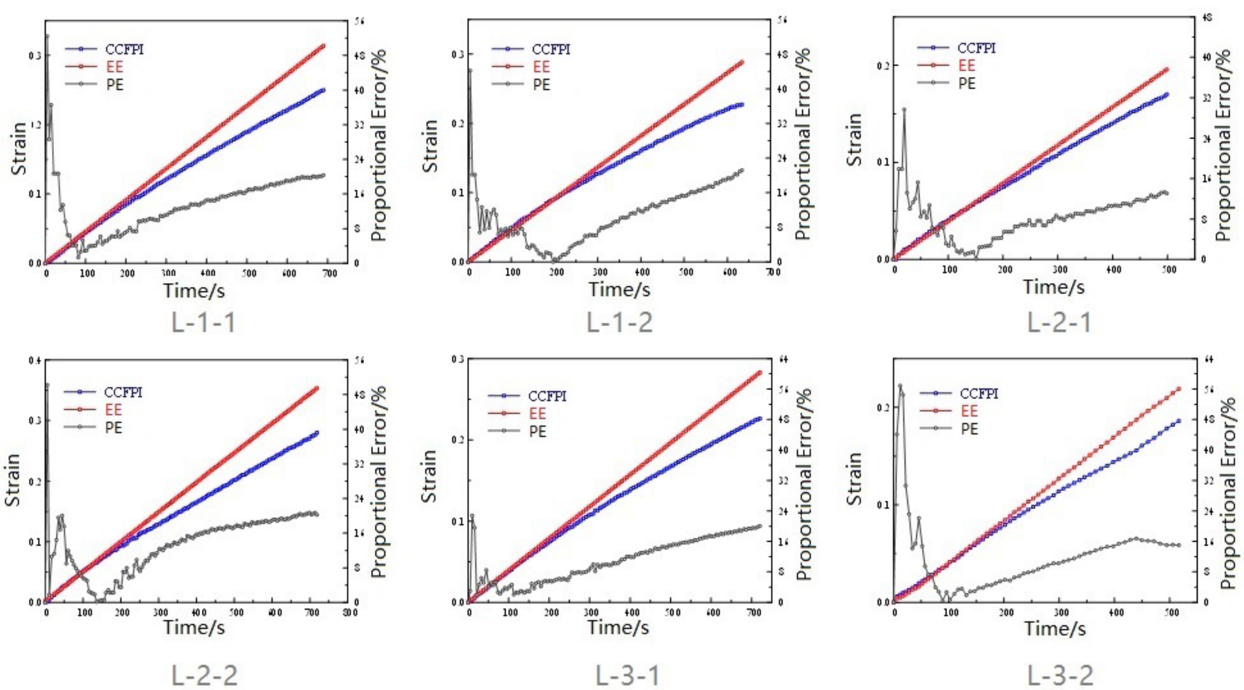

Fig. 5. CCFPI strain sensor vs. EE under different reflection point distances

between the two also showed a gradual increase. This was because the sensor gradually failed as the it was stretched, and the sensor diameter became smaller due to the stretching of the cable, which caused the coaxial cable slide slightly at the chuck, which was reflected in a gradual increase in the strain difference between the two.

3.2 Effect of Reflection Point Distance

In engineering applications, the distance between reflection points can affect the spatial resolution of the sensor to a certain extent. This is mainly because the corresponding reflection peaks overlap when displayed in the time domain on the vector network analyzer, so the reflection peaks corresponding to the two reflection points cannot be identified, and therefore the sensor data cannot be interrogated. Therefore, it is necessary to investigate the effect of reflection point distance on the characteristics of the coaxial cable strain sensor.

Fig. 5 gives the strain-time relation during the test and proportional error curve for the CCFPI strain sensors under different reflection point distances. Similar to the test results under different pretensions, the strain measured by the sensor (in blue) at the beginning of the test was basically consistent with the strain measured by the electronic extensometer (in red). As the test progressed, the strain measured by the sensor was significantly smaller than the strain measured by the electronic extensometer, and the proportional error between the two also showed a gradual increase.

3.3 Effect of Loading Rate

For the CCFPI strain sensor to be applied to various fields, strain monitoring under various experimental conditions will have higher requirements. From the perspective of the deformation rate generated by the measured substrate, the sensing characteristics of the CCFPI strain sensor at different loading rates are studied.

Fig. 6 gives the strain-time relation during the test and proportional error curve for the CCFPI strain sensors under different loading rates. The results are very similar to the test results under different pretensions and reflection point distances. Specially, when the loading rate was 0.02 mm/s, the strain curve measured by the sensor increased step by step. This is because the loading rate was too low, so the strain generated on the coaxial cable sensor was small, and in turn, the frequency offset of the spectrum was small, making the vector network analyzer unable to identify the change. This problem can be solved by using a vector network analyzer with higher peak power pulse measurement. This phenomenon disappeared when the loading rate continued to increase to 0.05 mm/s.

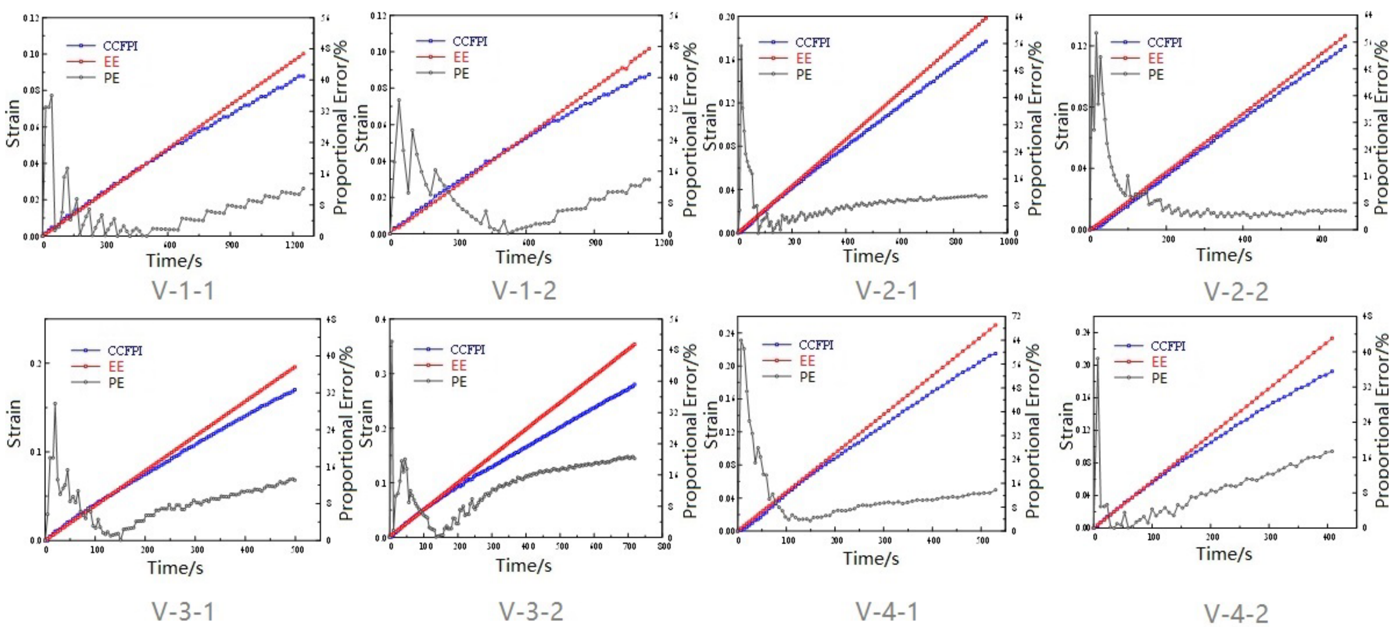

Fig. 6. CCFPI strain sensor vs. EE under different loading rates

4. DISCUSSION

The results showed that pretension has an influence on the sensor measurement range. The effective strain range gradually decreased as the pretension increased from 70N to 130N. This is because the failure of the sensor was caused by the fracture of the outer conductor of the sensor. As the pretension increased, the peak strain at the sensor fracture failure decreased. Although the resolution is not the same, this is due to the fact that it is impossible to guarantee that each CCFPI strain sensor is completely consistent when the sensors are homemade.

Reflection point distance has no effect on the sensor measurement range and resolution. The effective response range was basically constant as the distance between reflection points increased from 10 cm to 12 cm. This was because the increase in the spacing between reflection points only caused the spectral map to shift to the left without affecting its sensing performance. The results were consistent with the theoretical analysis based on the sensor working mechanism.

Loading rate has limited effect on the sensor measurement range and resolution. As the loading rate increased, the effective response range of the sensor showed a gradual increase, but as the loading rate increased to a certain extent, this increased trend gradually slowed down.

5. CONCLUSIONS

For CCFPI strain sensor fabricated with flexible RG58 coaxial cable, the laboratory test results showed that among pretension, reflection point distance and loading rate, only pretension affects the measurement range of the sensor. The larger the pretension, the smaller the measurement range of the sensor. Reflection point distance and loading rate have very limited effects on the sensor measurement range and resolution.

The results proved that the CCFPI strain sensor has engineeringly accepted accuracy and almost real-time response to the dynamic loads applied during the test. And the sensors have large measuring range (up to 10,000 $\mu\varepsilon$ in the tests) due to its excellent ductility, which further proves that the sensors can be as a feasible solution to carbon sequestration project monitoring strategies, and is of great value in providing early warnings of failure.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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