Invited Paper: Investigating Combined Effects between Dynamic Mechanical Loads and Corrosion on Epoxy Coated Steel Using Distributed Fiber Optic Sensors

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ABSTRACT

Each year, the global cost that is accounted to corrosion was estimated at $2.5 trillion. Corrosion not only imposes an economic burden, when corroded structures are under various loading conditions, it may also lead to structurally brittle failure, posing a potential threat to structural reliability and service safety. Although considerable studies investigated the combined effect of external loads and structural steel corrosion, many of the current findings on synergetic interaction between stress and corrosion are contrary. In this study, the combined effects of dynamic mechanical loads and corrosion on epoxy coated steel are investigated using the distributed fiber optic sensors based on optical frequency domain reflectometry. Experimental studies were performed using the serpentine-arranged distributed fiber optic strain sensors embedded inside the epoxy with three different scenarios including the impact loading-only, corrosion-only, and combined impact loading-corrosion tests. Test results demonstrated that the distributed fiber optic sensors can locate and detect the corrosion processing paths by measuring the induced strain changes. The combined impact loading-corrosion condition showed significantly accelerated corrosion progression caused by mechanical loads, indicating the significant interaction between dynamic mechanical loading and corrosion on epoxy coated steel.

Keywords: Corrosion; Dynamic mechanical loads; Interaction; Distributed fiber optic sensors (DFOS); Optical frequency domain reflectometry (OFDR); Strain distribution.

1. INTRODUCTION

Corrosion-induced structural deterioration is a significant concern in civil infrastructure, as it poses a serious threat to the durability, reliability, and safety of engineering structures [1]. Reinforced concrete and steel are commonly used construction materials that are vulnerable to corrosion, especially when exposed to environmental factors such as moisture, oxygen, and pollutants. Corrosion can lead to weakening, cracking, and even failure in structures, which can result in catastrophic consequences, including loss of life, property damage, and safety hazards [2]. To prevent and retard corrosion, various protective measures, including cathodic protection, corrosion inhibitors, anti-corrosion alloys, and coatings, have been developed and applied. Typically, epoxy coatings are the most widely used anti-corrosive coating for steel corrosion protection, providing a thin layer of isolation between the substrate and the external corrosive environment [3]. However, the performance of epoxy coatings can be affected by a variety of factors, such as the quality of the substrate surface preparation, the thickness of the coating, and the environment in which the coating is applied. Thus, in epoxy-coated steel, localized corrosion has the potential to occur under the coating. Localized corrosion can lead to the formation of pits and crevices, which are difficult to detect and can compromise the protection protected by the coating. Corrosion monitoring can detect the onset of localized corrosion and enable early intervention before severe damage occurs.

There are various techniques available for monitoring corrosion in steel and reinforced concrete structures, such as electrochemical impedance spectroscopy (EIS), linear polarization resistance (LPR), galvanic coupling sensors, and ultrasonic testing [4-6]. Compared with these traditional sensing methods, fiber optic sensors (FOS) have emerged as a promising technology for corrosion detection due to their numerous advantages, including high sensitivity, high durability, non-intrusive, multiplexing capability, real-time monitoring, and cost-effective [7]. Thus, FOS has become an attractive option for ensuring the safety and durability of structures in a variety of industries. Especially, fiber Bragg grating (FBG) sensors have been widely used for corrosion monitoring [8]. FBG sensors can be used to detect localized corrosion by monitoring the strain changes caused by the formation of corrosion pits. When the pit forms, it causes a local strain concentration, which can be detected by the FBG sensor. Moreover, corrosion-induced stress is a common problem in steel structures, which may lead to cracking and failure. FBG sensors can be used to monitor the corrosion-induced stress changes, allowing for early detection of potential failure. However, FBG sensors are point sensing, which are limited in the application of large-scale structures. In comparison, distributed fiber optic sensors (DFOS) can cover larger areas of a structure, providing a more comprehensive monitoring of corrosion activity compared to point sensors [7]. Besides, DFOS can provide continuous and real-time monitoring of multiple parameters simultaneously, such as strain, temperature, and vibration, along the entire length of the fiber optic cable, enabling a more complete understanding of structural health. Therefore, DFOS has emerged as cutting-edge and compelling sensing technology for structural health monitoring (SHM) [9].

On the other hand, external mechanical loads can cause stress concentrations and localized damage in structures, which in conjunction with the effects of corrosion, can significantly exacerbate the rate and extent of damage. The degradation of steel due to corrosion weakens its structural integrity, rendering it more prone to failure under mechanical loads. Moreover, corrosion often occurs in concealed or inaccessible regions of a structural component, making traditional monitoring methods ineffective [10]. Therefore, it is essential to monitor structural damage under the interaction between mechanical loads and corrosion, which is a critical component of maintaining the safety and reliability of civil infrastructure. Furthermore, early damage detection can help to minimize maintenance and repair costs in the long term.

Thus, the primary goal of this study is to investigate the combined effect of dynamic external loads and corrosion on steel substrate. For this purpose, an experimental study was conducted on epoxy-coated steel specimens embedded with Optical Frequency Domain Reflectometry (OFDR)-based distributed sensors in a serpentine-pattern. Individual corrosion, individual impact load, and combined corrosion and impact load tests were performed to explore the effect of impact loads on corrosion behavior.

2. SENSING PRINCIPLE OF OFDR-BASED DISTRIBUTED SENSOR FOR CORROSION DETECTION

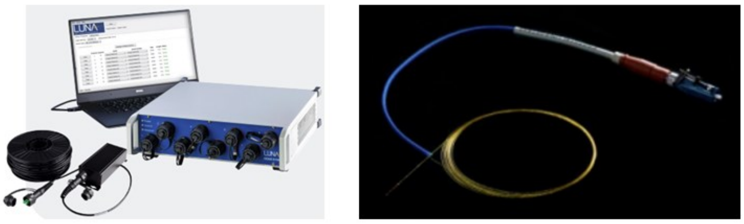
The Optical Frequency Domain Reflectometry (OFDR)-based distributed sensors utilize Rayleigh scattering, which occurs when a light wave interacts with the molecules in the fiber. As light travels along the fiber, a small portion of it is scattered back towards the source due to the inherent inhomogeneities in the fiber, such as impurities, variations in the refractive index, and structural defects. The scattered light contains information about the physical properties along the fiber length, including any changes in the refractive index or physical deformation caused by external factors such as corrosion. The backscattered light is collected by the same fiber and analyzed using a Fourier transform to determine the distribution of scattering points along the fiber. By continuously monitoring the corrosion-induced strain changes in the distribution of backscattered light over time, the OFDR-based distributed sensor can detect and localize the presence of corrosion on the steel surface.

The frequency shift in response to strain, ε, and temperature changes, ΔT, is described as [11]:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{v} = K_T \Delta T + K_\varepsilon \varepsilon \quad (1)$$

where λ and v are the mean optical wavelength and frequency; and K_T and K_ε are the temperature and strain calibration constants. For accurate strain measurement, a free fiber should be utilized to compensate for the effect of temperature changes.

In this study, an OFDR-based interrogator (Luna ODiSI 6100 series) along with a High-Definition (HD) Strain Sensor were used to acquire distributed data, as illustrated in Fig. 1. The mainframe is equipped with up to eight active measurement channels, each comprising a 50m standoff cable and a remote module. The interrogator utilizes OFDR technology to sense structural states by providing numerous sensing points with user-defined sensing locations and gauge lengths. The HD Strain Sensors, which are coated with polyimide, are available in different lengths ranging from 1m to 100m. 2m HD Strain Sensors were employed in the present experimental tests. And the gauge pitch and the measurement frequency of the distributed sensing system was set to 0.65mm and 1Hz, respectively.



(a) (b)

Fig. 1 Distributed sensing system: (a) ODiSI 6100 system, and (b) HD Strain Sensor (provided by Luna manufacturer).

3. EXPERIMENTAL PROGRAM

3.1 Materials and specimen preparation

Fig. 2 shows the designed ASTM A36 hot-rolled steel plate specimens with dimensions of 170mm×170mm×3mm. To secure the specimens on the test table, four 13mm diameter holes were punched on each corner of the steel plate. Before deploying the DFOS, the steel plates were cleaned with acetone. Then, a 2m distributed optical fiber was deployed on the steel plate with 11 sensing segments, each with a length of 100mm and a spacing of 10mm. Following the deployment of DFOS, a layer of Duralco 4461 adhesive epoxy with a thickness of 1.5mm was applied to safeguard the optical fibers against premature failure caused by impact loads. Upon completion of the manufacture process, the specimens were left to cure for a duration of 72 hours at an ambient temperature of approximately 24-27℃. This time period was deemed sufficient for the epoxy coating to attain the required level of hardness for the subsequent corrosion and impact loading tests.

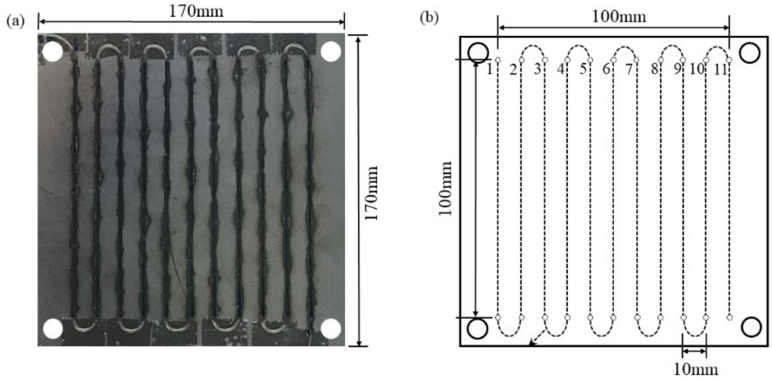


Fig. 2 (a) An example of the test specimen, and (b) deployment of HD Strain Sensor.

3.2 Test setup

This study aimed to evaluate the interaction between dynamic loading and corrosive environment on epoxy-coated steel. Three test groups were designed under individual impact load, individual corrosion, and combined impact load and corrosion, respectively, as shown in Fig. 3. The impact load was applied by dropping a 2kg calibration weight from 25mm height to the top surfaces of test specimens. A rubber tube was also used to maintain the consistent location of each impact loading test in the central area of each specimen. For the corrosion tests, 3.5% NaCl solution was employed to create corrosion environment, and artificial cracks were made to expedite the corrosion process. Furthermore, to explore the effect of impact loading on corrosion development, a combined test was carried out every six days during the 43-day corrosion process. As each test group consisted of 4 test specimens, with one specimen designed for temperature compensation, a total of 12 specimens were investigated, as listed in Table 1.

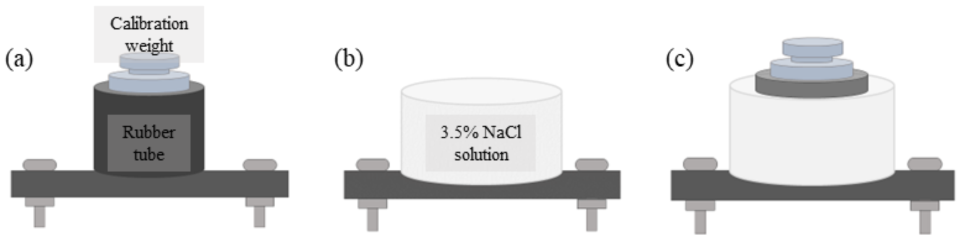


Fig. 3 Schematics of test setups: (a) impact loading test, (b) corrosion test, and (c) combined test.

Table 1 Specimens under three test groups.

Specimen	Test group	Total corrosion time T (day)	Impact height h (mm)
	Corrosion		-
C1		43	
C2		43	-

C3		43	
	Impact loading		-
I1		-	25.0
I2		-	25.0
I3		-	25.0
	Corrosion & impact loading		
C&I1		43	25.0
C&I2		43	25.0
C&I3		43	25.0

4. RESULTS AND DISCUSSIONS

The real-time monitoring capabilities of DOFS were demonstrated in comprehensively tracking the variation of corrosion development and distribution induced by impact loads. The results have shown that DOFS is a reliable tool for monitoring corrosion in structures. The corrosion distribution before and after each impact cycle for C&I1, C&I2, and C&I3 is shown in Fig. 4 to Fig. 6, respectively. The test phenomenon also provides valuable information about the corrosion process. Despite the premature damage to the DFOS before the 4th impact cycle test, the corrosion distribution profile detected by DFOS was still close to the profile observed in the visual inspection pictures. This indicates the potential of DFOS to monitor the entire corrosion process in real-time. Furthermore, the comparison of the corrosion area and severity before and after each impact cycle clearly showed that the impact load plays a significant role in the corrosion process, leading to increased corrosion rates and severity. The results suggest that the impact load exacerbates the corrosion process, making it more severe. Therefore, it is important to consider the impact load in designing structures to prevent corrosion. DOFS can be useful in monitoring corrosion development and distribution caused by impact loads in real-time, providing valuable information for the design and maintenance of structures. In addition, the results from Fig. 4 (g), Fig. 5 (g), and Fig. 6 (g) showed that C&I1 and C&I3 underwent the slowest and fastest corrosion, respectively, with the smallest and largest corroded areas. This suggests that the bonding performance of the coating was destructed by different degrees, indicating that the corrosion rate and severity are directly related to coating performance. The effectiveness of the coating in preventing corrosion is directly related to its bonding performance, which in turn depends on various factors such as the porosity and delamination of the epoxy coating. This finding is consistent with the conclusion in [12] that the corrosion rate is affected by the porosity and delamination of epoxy coating. Therefore, it is important to ensure the proper bonding of the coating to prevent corrosion in structures.

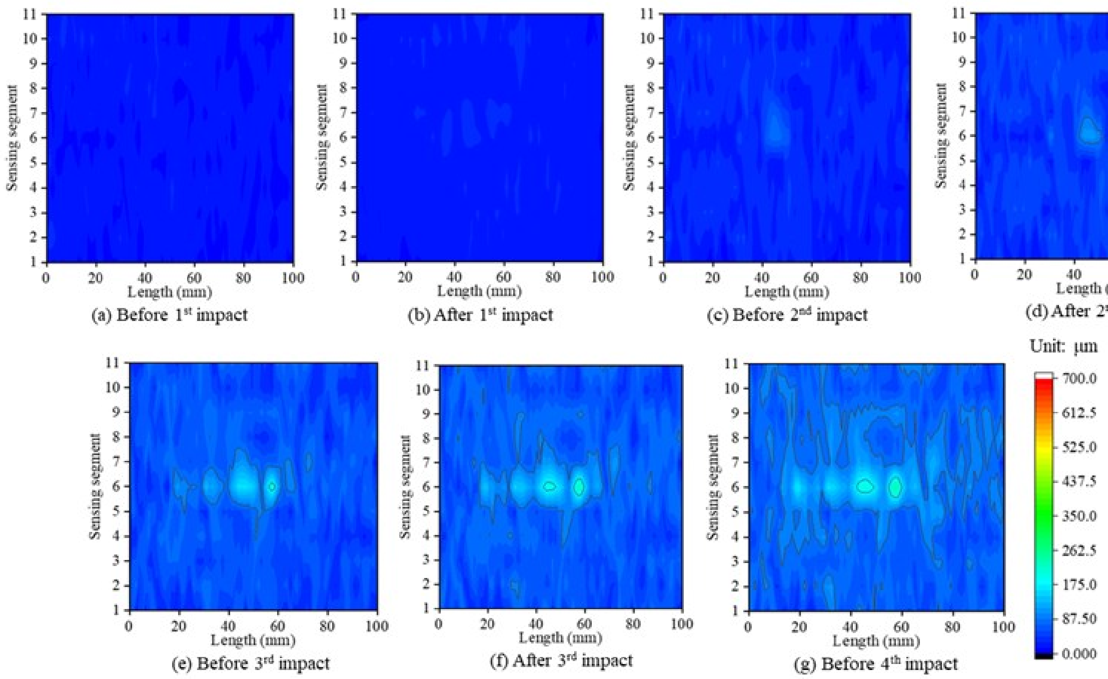


Fig. 4 Corrosion distribution of C&I1 before and after each impact test.

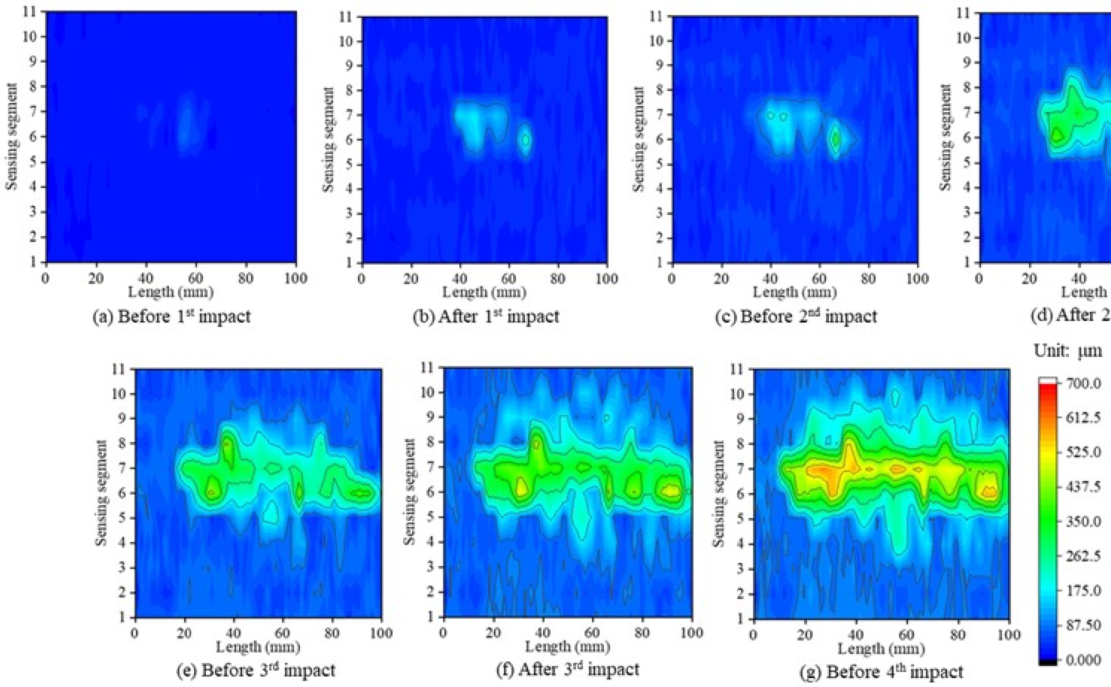


Fig. 5 Corrosion distribution of C&I2 before and after each impact test.

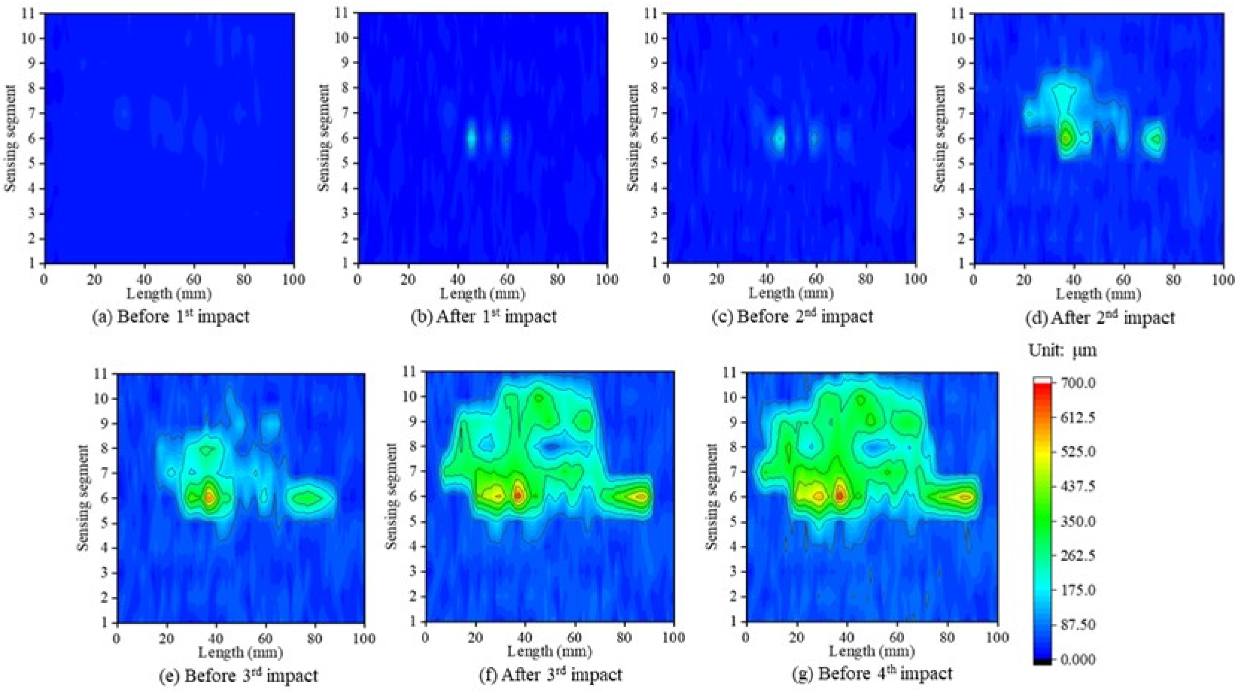


Fig. 6 Corrosion distribution of C&I3 before and after each impact test.

5. CONCLUSIONS

The results of this study have demonstrated the potential of DOFS as an effective tool for real-time monitoring of corrosion development and distribution caused by impact loads. This has important implications for the design and maintenance of structures that are susceptible to corrosion, as it enables engineers to detect and respond to corrosion-related issues in a timely manner. The findings also emphasize the significant role played by impact loads in exacerbating the severity of corrosion, which should be considered in the design and maintenance of structures. Furthermore, the results suggest that the bonding performance of the coating is a crucial factor in reducing the corrosion rate and severity. These findings could inform future research on coating design and maintenance strategies to prevent corrosion in structures. future research could explore the effect of other factors on the corrosion process, such as the environment and temperature. This could help identify additional factors that contribute to the corrosion process and inform the development of more effective corrosion prevention strategies.

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