Experimental Investigation of Corrosion Monitoring on Duplex-Coated Steel Utilizing Distributed Fiber Optic Sensors

Shuomang Shi[1], Luyang Xu[1], Xingyu Wang[1], Ying Huang[1]

1 Department of Civil, Construction, and Environmental Engineering, North Dakota State University, Fargo 58102

ABSTRACT

Civil engineering structures are routinely exposed to corrosive environments, posing threats to their structural integrity. Traditional corrosion control methods often involve employing physical barriers, such as various coatings, to isolate the steel substrate from surrounding electrolytes. Among these methods, thermal spraying of alloy coatings has emerged as a prominent technique in safeguarding steel matrices against corrosion, particularly in industrial and marine settings. However, the inherent porosity of thermal spraying coatings compromises their corrosion resistance. Incorporating a polymer top layer offers a promising solution by sealing pores and augmenting overall performance. This study investigates corrosion on duplex-coated steel utilizing distributed fiber optic sensors based on optical frequency domain reflectometry. Experimental analyses involve embedding serpentine-arranged distributed fiber optic strain sensors within both thermal spraying layers and epoxy layers. Results demonstrate the efficiency of distributed sensors in identifying corrosion propagation paths by measuring the induced strain changes. Furthermore, the duplex coating exhibits significant enhancements in corrosion resistance for steel structures.

Keywords: Duplex coating; Corrosion; Fiber Bragg grating (FBG); Distributed fiber optic sensors (DFOS); Optical frequency domain reflectometry (OFDR); Strain distribution.

1. INTRODUCTION

Structural integrity is frequently jeopardized by mechano-chemical effects, stemming from the interplay of mechanical loads and chemical assailants, notably corrosion [1], [2]. Among these threats, corrosion poses a significant hazard to steel-based civil structures, including plates, reinforcing bars, and prestressed tendons, hastening their deterioration and diminishing their longevity [3], [4]. Triggered by moisture and oxygen, corrosion instigates an electrochemical process that erodes the thickness and cross-section of steel elements within structures, impairing their load-bearing capacity [5]. In reinforced concrete structures, corrosion induces rust formation, fostering cracks in the concrete and further compromising load-carrying capability [6]. Coastal structures are especially vulnerable to severe corrosion due to elevated humidity and salinity levels. Nonetheless, corrosion presents a pervasive challenge for various civil structures like bridges and pipelines, which also contend with mechanical loads [7], [8].

Currently, thermal spraying hard coatings have emerged as a prominent method to prevent and alleviate corrosion across a spectrum of substrates, encompassing steel, aluminum, and ceramics, rendering them applicable across diverse industries. These coatings offer superior protection against corrosion by virtue of their dense and impermeable structure, serving as a barrier against corrosive agents. Moreover, they demonstrate exceptional adhesion to substrate materials, ensuring sustained durability and resistance against delamination or spalling [9]. Thermal spraying allows for the customization of coatings with tailored properties such as hardness, thickness, and composition, catering to specific corrosion resistance requirements in varied environments [10]. Nonetheless, thermal spraying coatings may inherently exhibit porosity, potentially serving as conduits for corrosive agents to infiltrate and affect the substrate material, thereby diminishing the efficacy of corrosion protection [11]. To address this vulnerability, sealing these pores with a polymer layer proves instrumental in obstructing pathways for moisture, oxygen, and other corrosive elements, thus fortifying the overall corrosion resistance [12]. Polymers employed as top layers in duplex coatings furnish exceptional barrier properties against corrosive agents, forming a continuous and impervious shield over the substrate surface [13]. This supplementary barrier layer augments the corrosion resistance conferred by the thermal spraying coating.

Hence, the principal objective of this study is to scrutinize the corrosion resistance performance of the developed duplex coating on steel substrate. To this end, an experimental investigation was undertaken on epoxy-sealed thermal spraying-coated steel specimens, augmented with Optical Frequency Domain Reflectometry (OFDR)-based distributed sensors arranged in a serpentine pattern within both coating layers.

2. Experimental program

2.1 Materials and specimen preparation

Fig. 1 depicts the arrangement of distributed fiber optic sensors on the tested steel plate specimens. A 5m distributed fiber optic cable was deployed on each specimen, following a serpentine pattern. Prior to sensor installation, the steel plate surfaces underwent thorough cleaning with acetone. Subsequently, the fiber optic cable was affixed to the steel plate at each U-turn point using tape, and each segment of the fiber optic sensing system was secured onto the steel plate using super glue. Following the sensor setup, a layer of thermal spraying coating was applied to the top surface of the specimen. Subsequently, a second layer of distributed sensors was deployed atop the hard coating surface, mirroring the deployment pattern of the initial layer of sensors. Finally, a thin layer of epoxy resin was employed to seal the metallized coating surface.

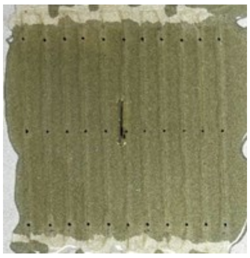


Fig. 1 An example of the test specimen embedded with distributed fiber optic sensors.

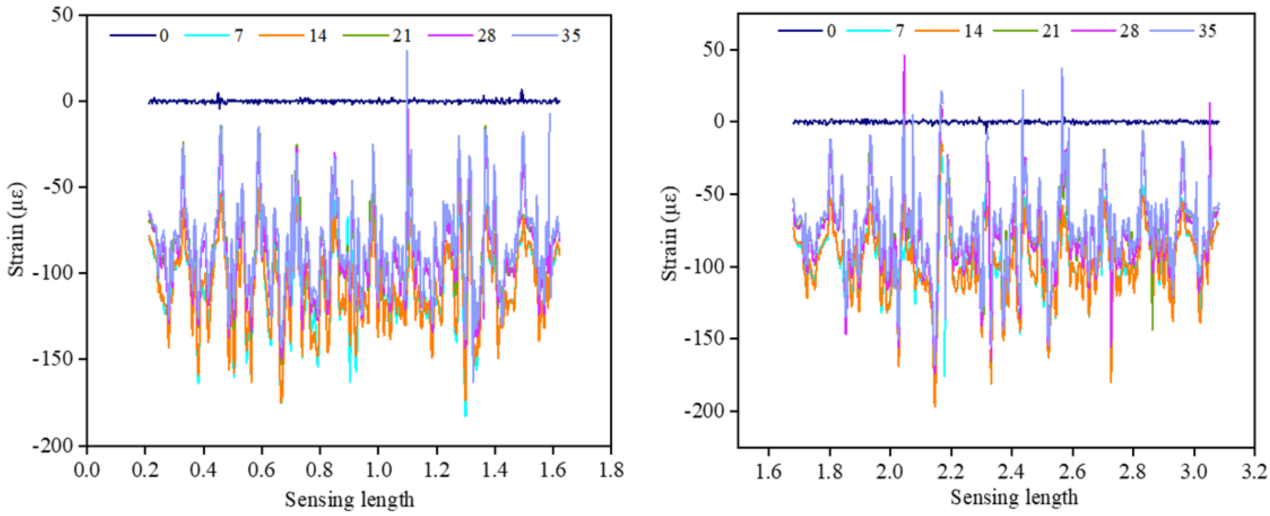
2.2 Test setup

This study aimed to assess the progression of corrosion on epoxy-sealed thermal spraying coated steel. Three samples, subjected to identical operational conditions, were arranged on a single steel plate, with one specimen designated for temperature compensation. To create an accelerated corrosion environment, a 100mm diameter PVC pipe was affixed to the central sensing area of the test specimen surface using epoxy resin, as shown in Fig. 2. Once the epoxy resin had cured, the PVC pipe was filled with a 3.5wt% NaCl solution to initiate corrosion tests conducted at room temperature (25°C±2°C). The experiment spanned 35 days to facilitate real-time corrosion monitoring through the embedded distributed fiber optic sensors.

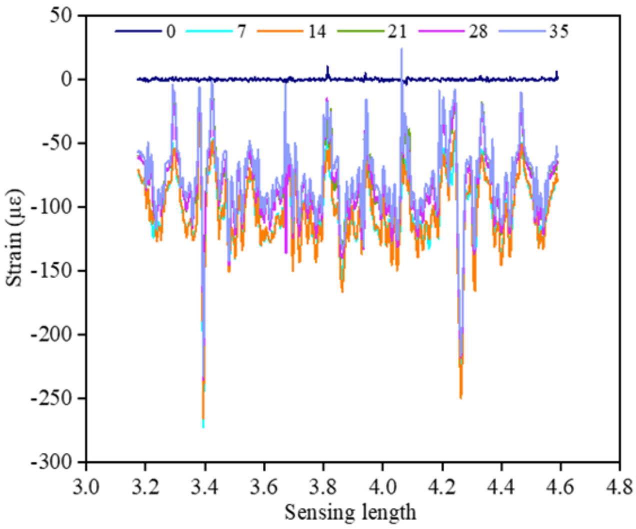
Fig. 2 Schematics of test setups: (a) impact loading test, (b) corrosion test, and (c) combined test.

3. RESULTS AND DISCUSSIONS

Fig. 3 illustrates the strain distribution within the distributed fiber optic sensor for the three test specimens, depicting the strain changes induced by pitting at six different time intervals (0 days, 7 days, 14 days, 21 days, 28 days, and 35 days). The measurement ranges of S1, S2, and S3 along the 5m distributed sensor spanned from 0.2126m to 1.6218m, 1.6816m to 3.0804m, and 3.174m to 4.5884m, respectively. Each sensing element was capable of detecting the severity and progression of pitting at its corresponding location by measuring the strain changes along the distributed sensor. The non-uniform strain distribution observed along the fiber can be attributed to the stochastic nature of pitting corrosion, resulting in irregular formation and accumulation of rust on the steel surface. However, the strain changes induced by corrosion across the three specimens remained relatively consistent, ranging between 0 and -150με, suggesting a similar extent of corrosion experienced by all specimens.



(a) S1 (b) S2



(c) S3

Fig. 3 Strain distributions along the distributed fiber under corrosion conditions.

4. CONCLUSIONS

The findings of this study underscore the efficacy of Distributed Optical Fiber Sensors (DOFS) in real-time corrosion monitoring, offering valuable insights for structural design and maintenance practices. The ability to promptly detect and address corrosion-related issues through DOFS technology holds significant implications for enhancing the durability and longevity of corrosion-prone structures. Moreover, our results highlight the pivotal role of the developed duplex coating in mitigating corrosion and bolstering resistance against environmental degradation. The observed reduction in corrosion rate and severity underscores the importance of the coating system as a key determinant in corrosion prevention strategies. Moving forward, further investigations could delve into the impact of additional factors such as environmental conditions and temperature on coating performance. Such inquiries have the potential to elucidate additional contributors to the corrosion process, thus informing the refinement of coating design and maintenance protocols to fortify structures against corrosion-related challenges.

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