Non-invasive Detection of Extent of Corrosion in Steel Reinforcing Bars by Magnetic Force Measurement

Durgesh Tamhane, Sauvik Banerjee, and Siddharth Tallur

1 Introduction

Corrosion of steel reinforcing bars in structures built with concrete leads to high repair costs and reduced serviceable lifetime of such infrastructure through the deterioration of the overall structural integrity. The extent of corrosion needs to be monitored, preferably by non-destructive inspection, to prevent costly repairs. Several non-destructive testing methods [1] based on techniques like ultrasonic testing [2], magnetic flux leakage [3], eddy currents [4] are employed today as a means of inspection of the structural integrity of civil infrastructure, with significant deployment toward the detection of internal corrosion [5].

One of the prominent issues today is the detection of corrosion of steel rebars inside reinforced cement concrete (RCC). Non-destructive techniques face several challenges, when applied to the detection of corrosion in RCC. These challenges include detection under an insulation layer and that of reliability of the detection process with varying ambient conditions, e.g., temperature variation. Accordingly, there is a necessity for a simple, practical and a non-destructive test that allows for easy and reliable assessment of corrosion of steel rods in RCC. Measurement of magnetic force to detect anomalies and defects in a ferromagnetic structure could fulfill this necessity.

Several techniques have been proposed for the detection of corrosion by exploiting the changes in ferromagnetic property of the sample due to corrosion. An inexpensive method [6] was proposed to extract information of corrosion in a non- or weakly ferromagnetic test objects by using a permanent magnet applied to the surface of

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the test object. By measuring the force required to detach the magnet from the test object (or by measuring the force of attraction with which the test object attracts the magnet), the carburization, nitriding, and chromium depletion in test objects was detected. A similar magnetic force based non-destructive testing apparatus [7] was proposed, where a sensor measures the interaction of an applied magnetic field and the sample to determine the extent of corrosion on the surface. A magnetic force sensor [8] based on a simple Fiber Bragg Grating (FBG), based on the principle of change of wavelength of light in response to the magnetic pull force was used to detect a natural corrosion pit formed in the bottom plate of a fuel storage tank. This sensor can detect cavity depths in the sub-millimeter range. Another magnetic force-based measurement [9] describes a ferromagnetic distance sensor based on the principle of fiber optic macro-bend loss. The motion of a magnet in response to the ferromagnetic sample couples to a pre-bent optical fiber and the change in the light intensity due to the bending of the optical fiber from its reference position was used to detect ferromagnetic metal loss due to corrosion. Another fiber optic sensor [10] was proposed that was applied as a strain gauge on a cantilever beam with a magnet at one end to detect internal metal loss in steel pipes and storage tanks where the authors have exploited the weak FBG nature of an optical fiber to respond to strain. The cantilever assembly similar to [7] on which the optical fiber resides functions as a strain gauge and measures the change in the thickness of a steel plate. The authors have also proposed another strain gauge for temperature compensation but have not included it with the measurement apparatus.

The constraints faced by non-destructive testing techniques mentioned above and elsewhere were to detect corrosion in ranges of depth in millimeter to centimeter range with or without an insulating coating over the test sample. In this work, we propose an apparatus and technique of detecting corrosion in the underlying steel rods of RCC structures. Our method, based on the detection of the change in the magnetic force exerted by a magnet on a cantilever, correlates to the varying degree of corrosion of the steel rods.

2 Method

In this work, a Wheatstone bridge circuit with a full-bridge strain gauge sensor configuration is employed to detect changes in magnetic force due to corrosion. The magnetic force exerted by a permanent magnet on the sample under test is proportional to the volume magnetic susceptibility, the area of the sample, the applied magnetic field and the distance of the magnet from the sample [11]. For a ferromagnetic material, like the steel bars used in RCC, this effect is more pronounced given the material has volume magnetic susceptibility of approximately $200,000$. Corrosion of these rods results in loss of ferromagnetic material, since the by-products of corrosion (oxides of iron) are not ferromagnetic. The material loss and the corresponding increase in the distance between the magnet and the steel bar due to the reduction in its diameter decreases the magnetic force with which the magnet attracts the steel bar. This magnetic force is measured using a temperature-compensated full-bridge strain gauge configuration mounted on a cantilever to give output as a voltage, which is proportional to the degree of corrosion in the steel rod. The voltage output across the full bridge configuration taken at various positions on the steel bar correspond to varying deformation of the cantilever due to magnetic force arising from varying degrees of corrosion along the length of the bar.

2.1 Experimental Setup

The fixture shown in Fig. 1 is designed to detect corrosion using strain gauges. This apparatus consists of a rectangular steel plate B fixed to an immovable base G by screws H. Four strain gauge sensors C, D, E, and F are fixed on the steel plate B. Strain gauge sensors E and F are fixed on top of the steel plate, while strain gauge sensors C and D are fixed on its bottom surface. A permanent magnet (here, a neodymium magnet) A is attached to the free end of the rectangular steel plate B. This setup forms an assembly equivalent to a cantilever beam with a point force applied to its free end. Figure 2 shows the steel rebar sample of diameter 20 mm used to test the detection apparatus. The sample has three distinct regions: non-corroded

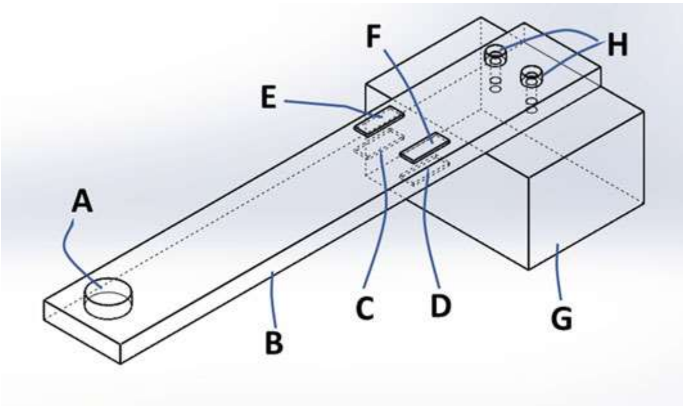


Fig. 1 The strain gauge fixture: *A* Neodymium magnet, *B*: Rectangular steel beam, *C, D, E, F*: Strain gauge sensors, *G*: Immovable steel base, *H*: Fixing screws

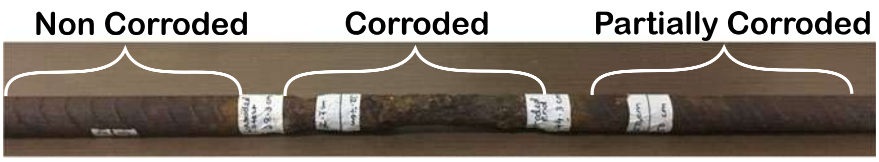
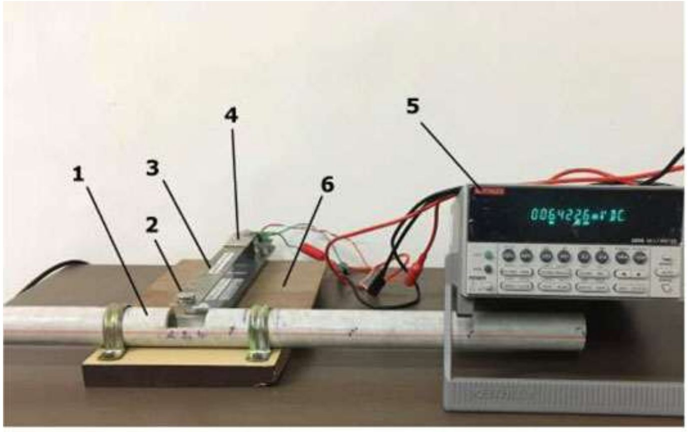
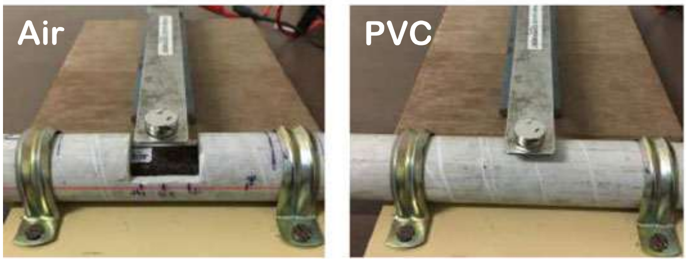


Fig. 2 Steel bar of 20 mm diameter with non corroded, corroded and partially corroded regions



(a)



(b)

Fig. 3 **a** Experimental setup: **1**: PVC pipe with a window cut-out *3*: Steel cantilever with *4* Strain gauges and *2*: Magnet, *5*: Digital multimeter (DMM), *6*: Wooden stage, **b** Left: The magnet on the cantilever is directly over the sample with only air in between, Right: The sample is under a 5 mm thick PVC coating

(left end), corroded (center), and partially corroded (right end) labeled accordingly in the figure. The apparatus depicted in Fig. 1 is then integrated into the complete experimental setup shown in Fig. 3a. A PVC pipe clamped to the wooden stage has a window cut-out, to allow either PVC insulation or air insulation between the magnet and the sample, as shown in Fig. 3b. The digital multimeter (DMM) is connected to measure the voltage output of the Wheatstone bridge configuration of the strain gauges.

The strain gauges C, D, E and F are connected in a Wheatstone bridge circuit with a full-bridge configuration, as shown in Fig. 4. Strain gauges E and F are mounted on the steel plate, and strain gauges C and D are mounted under the steel plate. This type of placement of the strain gauges and connecting them in full-bridge configuration improves the sensitivity of this system and also compensates for the ambient temperature variation. Under bending, the strain gauges E and F undergo

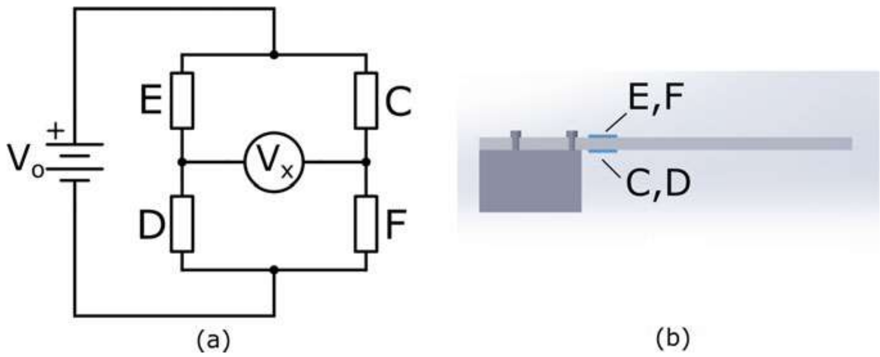


Fig. 4 **a** Block diagram of the system showing four strain gauges (C, D, E and F) in a Wheatstone bridge configuration. **b** The strain gauges C and D are mounted at the bottom, while E and F are mounted on top of the cantilever beam

tension, while strain gauges C and D undergo compression. The strain gauges are connected in the full-bridge configuration as shown in Fig. 4a. With V_x, V_0 being the measured and the bridge input voltage respectively, k, the gage factor and ε, the strain introduced due to the bending of the beam, the output of the bridge is given by [12]:

$$\frac{V_x}{V_0} = \frac{k}{4}\left[\varepsilon_{\mathrm{E}} - (-\varepsilon_{\mathrm{C}}) + \varepsilon_{\mathrm{F}} - (-\varepsilon_{\mathrm{D}})\right]$$

With $\varepsilon_{\mathrm{E}} = \varepsilon_{\mathrm{F}} = \varepsilon_{\mathrm{C}} = \varepsilon_{\mathrm{D}} = \varepsilon$, the measured voltage is

$$V_x = V_0 \cdot k \cdot \varepsilon$$

A +5 V DC voltage is applied across the full-bridge configuration, as shown in Fig. 4 using a DC power supply, and the differential voltage across the bridge is measured using a DMM with micro-Volt resolution. The strain gauges respond to the bending of the cantilever beam due to the force of attraction between the magnet and the steel bar. We record the voltage across the bridge without the sample and then with the sample inserted inside the PVC pipe, as shown in Fig. 2b. The first reading of voltage is recorded for the non-corroded region, followed by the voltage reading of the corroded and the partially corroded regions of the steel bar, and finally, a voltage reading is recorded with the rod removed. The measurements are performed by scanning the rebar along the pipe. Thirty such readings are repeated to acquire a statistically significant set of measurements. We repeat the above procedure for the steel rod with the 5-mm-thick PVC insulation coating in between the magnet and the steel rod sample.

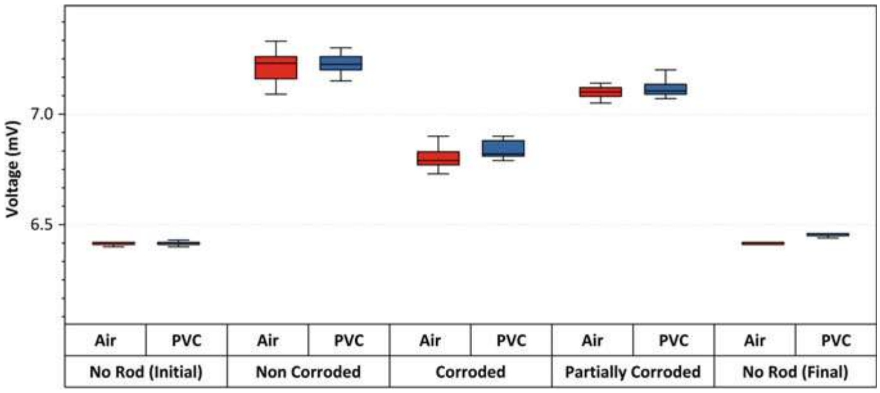


Fig. 5 Bridge voltage corresponding to the various corrosion states of the steel rod (with and without PVC insulation). The distinction in the sensor output for various regions is clearly observed

3 Results

Figure 5 shows the variation in the differential voltage across the bridge with respect to the degree of corrosion of the steel rod. The trend of decreasing bridge voltage for the corroded regions corresponds to reduced deflection of the cantilever due to the reduced magnetic force of attraction owing to loss of ferromagnetic material. The results do not show any significant effects of PVC insulation on the output voltage, and this technique is thus applicable to corrosion monitoring in insulated pipelines as well.

4 Conclusion

A concept of magnetic force of attraction of a magnet by ferromagnetic materials to detect the extent of corrosion in steel rebars is presented in this work. Detection of the degree of corrosion is achieved by measuring the output voltage across the full-bridge configuration of strain gauges mounted on a cantilever in a full-bridge, temperature-compensated manifestation. The measurement is insensitive to the presence or absence of PVC insulation over the sample and is thus applicable to corrosion monitoring in insulated pipeline use case as well. Our proof-of-concept demonstration suggests the ability of this setup to distinguish between different degrees of corrosion in several applications.

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