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Investigation of deterioration in corroding reinforced concrete beams using active and passive techniques

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HIGHLIGHTS

- Two elastic wave based NDT of active Ultrasonic Guided Waves (UGW) and passive Acoustic Emission (AE) are used to estimate degradation of corroding RC beams.
- Active UGW differentiates surface corrosion from pitting corrosion but it is not very effective in picking up initiation of corrosion.
- Passive AE exactly locates the regions of initiation of steel depassivation and progression of corrosion.
- Destructive testing of the corroded bars brings out the eminence of non-destructive monitoring in discerning different stages of corrosion in RC structures.

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ABSTRACT

Electro-chemical techniques that are routinely used in monitoring corrosion of reinforced concrete give an overall estimate of corrosion. Non-destructive techniques that are able to estimate the residual strength of corroding structures would help a great deal in strategizing post-corrosion maintenance. This paper explores two non-destructive techniques based on wave propagation for estimating residual strength of corroding reinforcement in concrete. The specimens undergoing corrosion were simultaneously monitored by acoustic emission (passive) and ultrasonic guided wave (active) techniques. The specimens were instrumented with AE sensors to record acoustic activities inside the specimens during corrosion. Simultaneously, the bars are also monitored by propagating ultrasonic waves through the bars. Active and passive monitoring results are correlated with already established electrochemical techniques to determine the relative efficacies of the NDT technologies. At the end of the exposure, the residual strength of the bars has been determined by tensile testing.

1. Introduction

Corrosion of reinforcement is one of the principal causes of premature failure of reinforced concrete (RC) structures [1]. In India, the annual loss due to corrosion has been estimated about 4% of the country's domestic product i.e., about USD 40 billion in a year in both infrastructure and industry segments. Non-destructive evaluation of residual capacities of reinforcements would help a great deal in devising a post-corrosion maintenance strategy of RC structures. Exposure to extreme environments and the continuous ingress of chlorides in concrete from various sources neutralises the protective passive layer of concrete which is alkaline with a pH ranging from 12 to 13 [2–7]. The presence of moisture and oxygen leads to the formation of oxides and the initiation of reinforcement corrosion takes place. Corrosion of reinforcement in concrete affects the durability of the RC structures in two ways: the formation of rust products with larger volume than steel leads to spalling and the cracking of the concrete cover; and the area of cross-section of the steel bars reduces drastically due to dissolution of the steel leading to pit formation and hence, loss in the tensile strength and load carrying capacity of the structure [8–11].

The mechanism of corrosion of steel in marine conditions has been observed to have four phases [4] (Fig. 1). Phase 1 refers to the stage of initiation of corrosion wherein the deterioration of steel begins as soon as the protective passive layer disappears. In this phase, the intrusion of water and oxygen predominates the rate of corrosion in steel. However, the corrosion rate decreases

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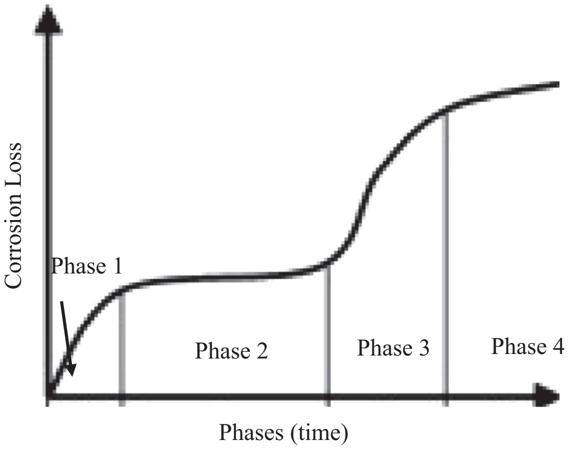

Fig. 1. Phenomenological model of corrosion loss in steel under sea water conditions [5].

subsequently, which may be due to the development of rust product protecting the steel. Further this impedes the steel-moisture interaction thereby restricting the corrosion activity (Phase 2). As the corrosion progresses further, the barrier layer of rust dissolves and the corrosion activity increases considerably represented by Phase 3. Thereafter, corrosion progresses almost at a constant rate and is represented by Phase 4. The coherence of this model with actual mechanism of corrosion in RC structures still needs to be researched.

Many advancements in the field of non-destructive corrosion monitoring techniques have been reported recently. In the field, visual inspection has remained the most popular technique for monitoring corrosion, although a host of Non-Destructive Techniques (NDT) is attempted by researchers [12]. When visual inspection can detect corrosion of concrete the overall strength of RC might be compromised. Electrochemical methods are qualitative in nature [12–14]. They provide information about the likelihood of corrosion but are unable to estimate the rate and extent of corrosion and the loss of capacity thereof. Some advanced methods like electro-magnetic methods suffer from the limitation of attenuation of the travelling waves due to accumulation of rust. The infrared tomography technique offers a qualitative analysis of damage due to corrosion but fails to quantify it due to corrosion. Strain sensing methods such as fibre optic sensors are able to monitor localised states of strain only [12]. Also, these methods suffer from practical limitations of restrained access and large dimensions of civil engineering structures which limit their usefulness.

Recently, wave based techniques having the ability to monitor RC structures by observing the variation in wave characteristics due to corrosion have been explored. Depending upon the method of application and monitoring, the wave techniques can be classified as active or passive monitoring techniques. Active monitoring techniques such as ultrasonic pulse and receive technology, involve the external excitation of a wave into the structure to be monitored and studying the variation in its propagation characteristics with damage. The transmitted or the reflected wave changes due to corrosion. Hence, they can be related to discontinuities or damages. On the other hand, passive monitoring techniques such as acoustic emission, involve the use of sensors on the structure without external excitation and listening to the changes inside the structure with damage progression.

There have been recent developments in the wave based technologies for corrosion monitoring in RC structures. Amongst active methods, Ultrasonic Guided Wave (UGW) monitoring has gained popularity for detection corrosion in reinforcing steel bars [15–24]. This method involves the introduction of high frequency wavelet packet or pulse into the structure and then observing the transmission and the subsequent reflection of these waves. The steel bar acts as the waveguide assisting its propagation. The characteristics of the transmitted or reflected waves change due to deteriorations in the bar because of corrosion. Two common effects of debonding and pitting in rebars due to corrosion in concrete affect the elastic wave propagation and the change in signal strength is related to corrosion. Both low frequency (50 kHz & 150 kHz) and high frequency (1 MHz) signals were utilised to study the delamination or debonding and it was reported that UGW has the potential for monitoring deterioration of the steel-concrete interface [15,16]. Further, different longitudinal modes of high and low frequencies were utilised to monitor damage in reinforced mortar specimens subjected to corrosion and it was suggested that low frequency mode was more sensitive to bond deterioration and loss in mortar [17]. In another study, only high signal frequency was used for monitoring corrosion in reinforced mortar and it was reported that the mode is highly sensitive to pitting accompanied by the loss of cross-sectional area of the reinforcement due to corrosion [18]. The authors have also suggested the use of specific low and high frequency guided wave modes through rebars in concrete to pick up delamination and pitting effects of corrosion in RC beams [19,20]. The method was extended successfully to identify type, rate and the mechanism of corrosion in RC structures [21]. The efficacy of different corrosion protection methods [25] and monitoring the setting process in different types of concrete, using ultrasonic guided waves has also been successfully demonstrated [22,23] by direct measurement of ultrasonic signals through embedded reinforcing bars in concrete. Ultrasonic guided waves have proven to be an effective health monitoring technique for RC structures.

Passive acoustic emission technique has been utilised in recent structures which listens and records the changes occurring in a structure due to stress redistribution as a result of damage inside the material, using surface mounted sensors. The received signals are known as Acoustic Emission (AE) events, which are transient elastic waves originating from sudden outburst of energy from localised sources within a material [25]. The main factors which influence the AE signals are source characteristics, path between the source and transducer, transducer characteristics and measuring system. AE has been used for detecting and localising the cracks arising from the initiation and progression of corrosion [26–29]. It has been demonstrated that AE can evaluate the early stage corrosion process in concrete due to the expansion of corrosion products. It has been also confirmed that AE activity related well with the onset of corrosion and nucleation of concrete cracking [30]. A new time driven data (TDD) based monitoring methodology to characterize the onset of corrosion using AE has successfully been reported [28]. Researchers have also compared electro-chemical measurements and AE and have shown that an agreement exists between them regarding the onset of corrosion in RC structures [27,31,32]. It has been suggested that electrochemical methods managed to evaluate the corrosive character of medium whilst the AE showed an activity characteristic of corrosion initiation phase and corrosion propagation [33]. Present authors have successfully reported a pilot study suggesting the use of a combination of UGW and AET for monitoring the onset of corrosion in RC structures much before it is visible on the surface of concrete. This technique is useful when the structures are not affected by corrosion. However, many structures have already suffered from extensive corrosion and an effective monitoring technique to estimate their condition is essential to decide on the prognosis of these facilities. This paper reports monitoring techniques for those structures with considerable corrosion. The focus is to investigate the applicability and effectiveness of monitoring different stages of initiation, pro-