Damage detection of artificial corroded rebars and quantification using non-destructive methods on reinforced concrete structure

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Abstract. Corrosion of rebars in reinforced concrete structure is a big universal problem created by saline water ingress causing rebar and other metal structural member to corrode. The deterioration of concrete structures due to the harsh environment conditions leads to the deterioration of the reinforced concrete performance structure, and the premature deterioration of the structure before completing due to carbonation or the chloride content of the future services is expected to be the primary concern for engineers and researchers. Progress of corrosion location cannot be visually evaluated until the point when crack or a delamination is appearing. Therefore, in the study, the Ground Penetrating Radar (GPR) is used to investigate the artificial rebar corrosion damage on steel rebars. The methods showed the artificial rebar corrosion damage can be detected and quantified without damaging the surrounding concrete material. GPR showed the potential on detecting rebar corrosion damage on large areas and in a rapid manner.

1. Introduction
Malaysia is one of the Asian countries that greatly depends on the sea and coastal areas to facilitate most of its economics and trading activities. It is reported that 95 percent of Malaysian international trades is contributed by its seaborne transport and coastal ports [1]. The availability of reinforced concrete (RC) infrastructures, i.e. bridge deck, long jetty structures and other marine wall structures are needed to expedite the growth of this trading activities over the sea and coastal areas. However, due to the aggressive sea water splashes on RC infrastructures, chloride attack will initiate the rebar corrosion after exceeding certain threshold chloride values; which later pose to premature structural safety and serviceability issues to its users once this corrosion process is not prohibited to progress [2].

Corrosion of rebars has become a serious “disease” and known as the worldwide widespread deterioration problem to RC. With this disease exist in RC structure, two main forms of material deterioration problems can be developed progressively. One of the most obvious deteriorations is the formation of fracture plane defect on concrete, i.e. concrete spalling, due to expansive force of corroded rebars to the surrounding concrete material. The fracture plane is greatly depending on concrete cover thickness and rebar spacing [3]. The depth of cover will control the form of corrosion cracking, either
to be inclined or horizontal cracks [4]. The second type of deterioration is the influence to the friction bonding between the interface of steel rebar and the concrete. The bond resistance on this interface was studied by reference [4], and it is a function of degree of corrosion. The average bond stress was found increased before corrosion level reached 2 percent and starts to decrease after 2 percent rebar corrosion level [5]. All these manifestations were eventually leading to the RC infrastructural damage and premature degradation before its intended design life ended. Therefore, several routine corrosion assessment inspections and maintenance program on coastal RC areas is urgently required to reduce and limit the corrosion-induced damage problem on RC.

The Non-Destructive Test (NDT) is an alternative method of RC inspection and maintenance program to access the state of corrosion damage risk on coastal RC structures without to disturb physically the structures due to its mobility and rapid manner execution. Various existing NDT methods that able to detect and access the rebar corrosion damage risk has been used by the engineers and researchers. Commonly, rebar corrosion assessments damage on RC infrastructures were conducted by electrochemical method [6], ultrasonic wave method [7], acoustic emission technique [8] and embedded piezo sensors [9]. However, these assessments methods have its own shortcomings. Electrochemical method will yield results that is commonly influenced by the variation of moisture content of the concrete [10], the concrete cover [11] and the room temperature [12] during corrosion assessment. Ultrasonic waves enable the detection of features of certain thickness [13] and require calibration on each tested material. Acoustic emission method showed weak signals when detecting pitting corrosion caused by localized anodic dissolution [14]. Embedded piezo sensors performance was found to be temperature dependent which cause some horizontal signature shift due to change to host’s material Young Modulus [15]. In view of this, a more reliable and efficient method is crucially required such as Ground Penetrating Radar (GPR).

This study aims to principally establish the more efficient method via the electromagnetic wave to detect and quantify the artificial rebar corrosion damage on a RC slab structure using the GPR. The usage of GPR is commonly used to map the large deteriorated RC areas by scanning continuously along the intended surface areas. The method is very efficient due low operational cost, fast and rapid data acquisition manner.

2. Methodology

2.1 Materials

One slab sample with the dimension of 0.8m × 0.5m × 0.2m was prepared with 40/45 concrete grade. The mix composition of the concrete is shown in Table 1. A total of five steel rebars was placed in the concrete at constant depth of 70mm based on maximum cover as set by durability requirement in Eurocode 2 [16]. Each rebar has been corroded artificially by accelerated corrosion test system (ACTS) under different corrosion damage severity specified by 0%, 10%, 20%, 40% and 60% reduction from its original diameter respectively. The fine aggregates were taken from natural river sand and the 10 mm coarse aggregate with an average density of 2.7 g/cm³. Clean tap water was used for the sample’s mixture.

| Material       | Cement (kg) | Water (kg) | Fine Aggregate (kg) | Coarse Aggregate (kg) |
|----------------|-------------|------------|---------------------|----------------------|
| Per m³         | 532.4       | 225.5      | 793.1               | 1094.5               |

2.2 Sample preparation

In this study, fabrication of formwork for the slab was custom made to allow penetration of rebar across the width of the sample. Silicone sealants were used to properly close gaps between wood planks. A motorized concrete mixer was used to batch the concrete mix for the study. Concrete casting was done immediately after mixing, with compaction via vibrating rod for every third of the concrete volume.
Once dry, a grid was drawn on the top surface of the sample for reference of the following tests. Formwork is then dismantled after 3 days and cured by soaking wet sacks over the sample. The sample is also placed over a wooden pallet for ease of lifting by forklifts. Figure 1 shows the schematic diagram of the prepared sample.

![Figure 1. Schematic diagram of the slab sample and its rebar corrosion damage.](image)

2.3 Accelerated corrosion test system

The steel rebars embedded in to the slab concrete sample were corroded artificially prior to casting. The usage of artificial corrosion mechanism is to shorten the real time-consuming corrosion process on the rebar that is not practical to be conducted on laboratory scale. The targeted to be corroded rebars were placed at the anode while the cathode can be any substitute metal. Figure 2 shows the ACTS used to pre-corrode the individual steel rebars before embedded in the concrete. Faraday’s Law of electrolysis was used to estimate the needed theoretical time of the rebar corrosion, t, as calculated from the Equation 1 [17].

\[
m = \left( \frac{It}{F} \right) \left( \frac{M}{z} \right)
\]

where

- \(m\) = mass of steel bar (g),
- \(I\) = electrical current (A)
- \(t\) = time of corrosion (s)
- \(F\) = Faraday’s constant (96500 C mol\(^{-1}\))
- \(M\) = molar mass of the steel
- \(z\) = valence
Figure 2. Accelerated corrosion test system used for corroding the steel rebars.

The time required for corrosion depends on the desired corrosion damage and current of the DC flow. Table 2 shows the corrosion damage of each bar with its respective time under accelerated corrosion.

Table 2 Time for accelerated corrosion to reach specific artificial rebar damage.

| Corrosion Level (%) | Initial mass (g) | Mass Loss (g) | Actual Mass Loss (g) | Actual time (hrs) | Current (A) |
|---------------------|------------------|---------------|----------------------|------------------|-------------|
| 0                   | 1659.7           | -             | -                    | -                | 50          |
| 10                  | 1656.7           | 165.67        | 150.8                | 5.98             | 50          |
| 20                  | 1660.4           | 332.08        | 305.07               | 12.35            | 50          |
| 40                  | 1657.9           | 663.16        | 649.91               | 40.63            | 50          |
| 60                  | 1658.5           | 995.1         | 1008.52              | 80.36            | 50          |

2.4 Data acquisition using GPR and Resistivity meter for detection of rebar corrosion damage

A commercially available equipment wheel-cart based, GSSI GPR SIR 3000 with central frequency of 1.6 GHz, was utilized in this study to collect the data in form of digital signals over a sample. A set of wooden tables were fabricated and placed at both sides of the sample to facilitate the GPR scanning on top of the sample. Calibration of the GPR measured horizontal distance and dielectric values were made initially by comparing it with the actual horizontal distance and standard material dielectric measurements [18].

The attenuation of GPR signal according to the corrosion percentage can be quantified by using Equation 2 as follows [19]:

\[
\alpha = \log_{10}\left(\frac{A_0}{A_t}\right) \tag{2}
\]

where;

\(\alpha\) = Attenuation coefficient, \(A_0\) = GPR signal amplitude with no corrosion damage.

\(A_t\) = GPR Signal amplitude at certain corrosion damage (both are in V)
3. Results and Discussions

3.1 GPR signal amplitude analysis (B-scan and A-scan)

GPR B-scans and A-scan were obtained by scanning the sample in one direction (left to right) and shown in Figure 3 and 4 respectively. From Figure 3, it is noted several electromagnetic reflections of each rebar were shown in form of inverted hyperbolas [20] with different brightness. It is apparently that the brightness of the inverted hyperbola of each rebar is increasing with the decreasing artificial rebar corrosion damage. These hyperbolic brightness phenomena is fully agreed with the finding by reference [21], where it was found GPR signal amplitude is decreasing with the increasing percentage loss in his tank experiment.

![Figure 3. Inverted hyperbola formation for each artificial corrosion rebar.](image)

![Figure 4. Negative Amplitude Profiles of Rebar Corrosion Damage (A-scan).](image)

Figure 4 showed the negative signal amplitude at the top surface of each rebar which is denoted as $A_0$, $A_1$, $A_2$, $A_3$, $A_4$ and $A_5$ according to its artificial rebar corrosion damage. The signal amplitude attenuation was fitted non-linearly using the third order polynomial curve fitting with the best coefficient of determination of 0.9993 as shown in Figure 5. Similar pattern of the relationship between the GPR signal and rebar area lost were shown by [22], however the later showed a linear trend relationship. This difference of the relationship trend between the former and later study is possibly due to the dissimilarity in propagation medium used for embedding the corroded rebar in both studies.
3.2 GPR signal attenuation analysis

Based on Equation 2, the GPR signal attenuation of each artificial rebar corrosion damage was computed and its relationship is plotted in Figure 6. It is noted that the GPR signal attenuation, $\alpha$, is increased exponentially with the increasing artificial rebar corrosion damage, showing the high GPR signal attenuation variation to the changes of rebar corrosion damage. It is hypothesized that there is no signal attenuation when there is no corrosion of rebar in this study. This signal attenuation characteristics is greatly influenced by size of the rebar relative to the electromagnetic wave length field emitted by the GPR transmitter. Slight corrosion damage on rebar will return a smaller reflected signal compared to the intermediate rebar corrosion damage. Therefore, the severe rebar corrosion will reflect more weaker signals than that of intermediate corrosion; thus, results in smaller amplitude results for small corrosion damage. Same results were obtained by reference [23] when assessing the rebar corrosion with GPR on highway structures by artificially reducing the rebar’s cross section to represent the corrosion effect. Reference [23] reported that corroded rebars attenuate the GPR signal amplitude more than the uncorroded rebar due to the rebar diameter reduction due to the corrosion process. Another research work observed that GPR amplitude wave attenuation for 16 mm rebar showed the rapid GPR signal attenuation pattern as the rebar corrosion damage is increases during the first 61 days [24].

![Figure 5](image-url)  
**Figure 5.** Relationship between the GPR signal amplitude and the corrosion damage severity.

![Figure 6](image-url)  
**Figure 6.** Relation of GPR signal attenuation and artificial corrosion damage.
4. Conclusions
GPR serves as an alternative NDT technique on detecting and quantifying the corrosion levels of rebar in RC with rapid and under relatively low operational cost. Further on-site study is recommended to explore and verify the applicability of the relationships obtained in the laboratory scale to several RC coastal structures.

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