Construction and Building Materials 175 (2018) 351–359

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Quantitative study of electromagnetic wave characteristic values for mortar's crack

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HIGHLIGHTS

- Mortar specimens with inner crack of various depth are scanned by ground penetrating radar.
- Travel time and waveform characteristic of mortar crack are quantitatively evaluated.
- Correlation of Encoded signals is a subtle parameter to quantify inner crack.
- A available method based on correlation of signals to visualize inner crack is proposed.

ARTICLE INFO

Article history:
Received 7 May 2017
Received in revised form 25 September 2017
Accepted 26 September 2017

Keywords:
Ground penetrating radar
Crack
Wave encoded signal
Signal correlation

ABSTRACT

Horizontal 4 mm-thickness cracks with various depth in different cement mortar specimens simulate respectively various inner micro-defects. GPR antenna of 1.0 GHz and 2.3 GHz central frequency scans respectively the inner-cracked specimens and non-crack one. Electromagnetic waveform characteristic, travel time and correlation of encoded ground penetrating radar reflection signals are quantitatively evaluated. The electromagnetic waveform and its travel time from 2.3 GHz antenna appear distinct reflection characteristic at the interface of inner crack; while only transmission of electromagnetic wave is observed when 1.0 GHz antenna employed. The correlation coefficient of encoded signals, is an available parameter to depict quantitatively inner crack, based on which a brief method to visualize inner crack is promoted within average erroneous percentage of 6% in shallow crack when scanned by 2.3 GHz antenna.

1. Introduction

Ground penetrating radar (GPR) is widely employed in the various disciplinary field such as Structure Health Monitoring (SHM), Pipeline Leaking Inspection, Geophysical survey, Archaeological structure Maintenance and so on [1–5]. Recently, with the rapid promote of GPR data processing technology, the application of GPR is extensively being expanded to quantitative survey of rebar, corrosion, moisture content, durability and interior defects of the concrete structure and the like [6–13]. Most concrete members in-servicing are inner cracks, growth of which affects sensibly the structural integrity. Consequently, the detection of inner cracks is constantly a main focal point of SHM. But many influential factors such as survey environment, electromagnetic characteristic of structure members and the dimension of inner cracks, affect conspicuously the survey efficiency of GPR. While the inner cracks in concrete structure have been normally supposed beyond of the resolution scope of GPR. Thus, quantitative detection of micro-defects in structural members employing GPR is mostly confined to the resolution of large scale defect in concrete such as void and honeycomb, or only to numerical simulation through Finite Difference Time Domain or Finite Element Method [14–19], the result of which usually more theoretical than the inspection of on-site. Meanwhile other Non-Destructive Detecting (NDT) methods, like Ultrasonic or Impact-Echo method, are deployed to measure tiny concrete cracks sometimes [20], but lots of disadvantages such as stern survey environment condition, intricate operation and relative high cost, inevitably restrict its application on-site. A convenient method is required to be developed to quantitatively detect inner micro-defect in concrete utilizing GPR, through which multi-objective data interpretation is easily performed by single-scan on-site.

2. Methodology

2.1. Algorithm (Ground penetrating radar)

Ground penetrating radar has been a well-accepted NDT technique. The method employs electromagnetic (EM) wave to probe "the structural member" that means any low dielectric material.

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https://doi.org/10.1016/j.conbuildmat.2017.09.171
0950-0618/

GPR measurement deploys a transmitter and a receiver, which are shifted over the surface of structural member to inspect reflection from subsurface characteristic. With the variety of inner defects characteristic, electric-field strength, EM waveform and EM pulse propagation path will alter resultantly. The variation of two-way travel time, amplitude or/and frequency of reflection wave are measured. Then the dielectric permittivity, velocity or other dielectric parameters are calculated to evaluate the condition of inner defects. ASTM D6432-11 [21] recommends the following Eqs. (1) and (2) to evaluate EM wave velocity or dielectric permittivity.

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

where:

c = propagation velocity of EM pulse in free space (3 × 108 m/s),
v = propagation velocity of EM pulse through the inspected material of structure members, and
ε_r = relative permittivity of the inspected material of structure member.

$$t = \frac{2D}{v} \tag{2}$$

where:

t = two-way travel time of an EM pulse in structure members,
D = measured depth to reflecting interface in structure members, and
v = propagation velocity of EM pulse through the inspected material of structure members.

Two-way travel time, t, not only reflects the properties of inspected materials, but also is a crucial parameter to resolve the material characteristic especially when measured depth is given. While the sample numbers within a given depth of "the structure" depict directly the travel time of an EM pulse propagation with a specified time window.

2.2. Signal correlation

Statistically, correlation coefficient is utilized to compare the similarity between two signals. The normalized correlation coefficient, ρ_{xy}, is calculated from the relationship as follows:

$$\rho_{xy} = \frac{\gamma_{xy}}{\sigma_x \sigma_y} \tag{3}$$

where:

x = abbreviation of a time-serial encoded signal x_t,
y = abbreviation of another time-serial encoded signal y_t,
ρ_{xy} = normalized correlation coefficient of encoded signal x_t and encoded signal y_t,
γ_{xy} = the covariance between encoded signal x_t and encoded signal y_t,
σ_x = the standard deviation of encoded signal x_t, and
σ_y = the standard deviation of encoded signal y_t.

The value of ρ_{xy} lies between −1 and 1, and closer to zeros, the more different the two signals. And in Eq. (3), the covariance, γ_{xy}, could be calculated Eq. (4).

$$\gamma_{xy} = E[(x_t - \mu_x)(y_t - \mu_y)] \tag{4}$$

where:

x = abbreviation of a time-serial encoded signal x_t,
y = abbreviation of another time-serial encoded signal y_t,
γ_{xy} = the covariance between encoded signal x_t and encoded signal y_t,
E [] = an expected value of an encoded signal,
μ_x = the means of encoded signals x_t,
μ_y = the means of encoded signals y_t,

$$\sigma_x = \sqrt{E[(x_t - \mu_x)]^2} \tag{5}$$

$$\sigma_y = \sqrt{E[(y_t - \mu_y)]^2} \tag{6}$$

where:

x_t = a time-serial encoded signal,
y_t = another time-serial encoded signal,
σ_x = the standard deviation of encoded signal x_t,
σ_y = the standard deviation of encoded signal y_t,
E [] = an expected value of an encoded signal,
μ_x = the means of encoded signals x_t, and
μ_y = the means of encoded signals y_t.

Correlation between two GPR signals respectively scanned from different position of structural member demonstrates the similarity of the above two positions. If one signal is scanned from the sound part of structural member and the other signal is scanned from a degraded member, the correlation coefficient of two signals indicates the degree of degradation of the member. The lower of correlation coefficient, the high possibility of degradation of structural member. Then the space position of inner defects in structural member is depicted through the correlation coefficient between encoded signals from various depth in structural member. Fig. 1 shows the numbered traces in various specimens.

From the left scanning point along scanning direction, the signals of traces in non-crack specimen (TN, for short) are numbered as $TN_1, TN_2, \ldots, TN_i, \ldots, TN_n$ in turn, where n denotes total numbers of traces in non-crack specimen within the scope of specimen width. TN_i means the i-th trace from start point of scanning within the scope of non-crack specimen width. The signals of traces in inner crack specimen (TC, for short) are numbered as TC_1, TC_2, …, TC_j, …, TC_n in turn, where n denotes total numbers of traces in inner crack specimen within the scope of specimen width, being equal to the total numbers of traces in non-crack specimen scanned by the same antenna. TC_j means the j-th trace within the scope of inner crack specimen width. And d_k means the k-th scope of depth to be resolved.

As showed in Fig. 1, given d_k, the correlation coefficient between the trace TN_i and the trace TC_j, depicted as ρ_{ij}, is calculated from Eq. (3). And the vector of correlation coefficient (MC_k) is obtained, as showed in Eq. (7), where k corresponds to specified inspection depth d_k.

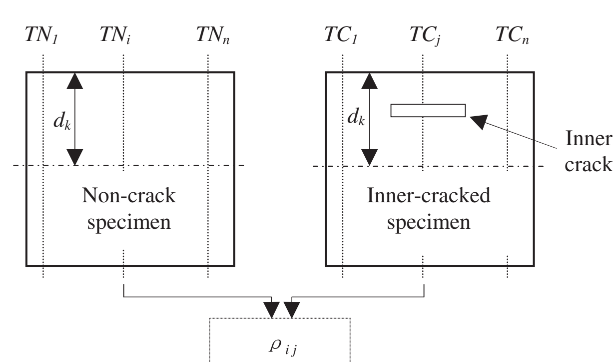

Fig. 1. Encoded signals numbered in various specimens.