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# Numerical and experimental study on multi-directional SAFT to detect defects inside plain or reinforced concrete

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## HIGHLIGHTS

- We proposed a new imaging method to detect defects inside concrete.
- The generated image can reveal the geometry of defects.
- The proposed method can be used on plain or reinforced concrete.
- The demonstration was carried out in numerical and experimental aspects.
- Experimental results show good agreement with numerical ones.

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## ABSTRACT

This paper discusses the feasibility of detecting defects inside reinforced concrete (RC) structures by using multi-directional Synthetic Aperture Focusing Technique (SAFT) to create an image which contains the comprehensive information about the geometry of possible defects. This is achieved by scanning the structure in multiple directions and processing the response data with SAFT and proposed scheme so that the shape and the position of a defect or defects can be completely described. The demonstration was carried out in numerical and experimental aspects. Furthermore the correlation between the numerical and experimental results was analyzed in this paper.



## 1. Introduction

Among the common nondestructive testing (NDT) techniques used in civil engineering, those with applying elastic waves have been playing an important role on evaluating the integrity of concrete structures [1]. These methods were usually effective for on-site testing because of using the point-source/point-receiver scheme. One frequently used elastic-wave-based technique is the Impact Echo (IE) method. In 1992, Carino et al. transformed time-domain signals into those in frequency domain for resonance frequency of possible defects [2]. In 1995, Wu et al. developed a series of methods based on the elastic wave theory to evaluate the depth of surface cracks and the elastic constants of concrete [3–7]. These methods are effective at evaluating the integrity of concrete structures, yet only under advantageous conditions or for defects of simple geometry. In unfavorable environment, multi-directional evaluations may become a necessity.

The phase array system has long been used in medical ultrasonography. Since 1986, the Synthetic Aperture Focusing Technique (SAFT) has been adopted as a new signal processing strategy incorporated with ultrasonic method for testing metallic materials [8,9]. In 2001, Chang et al. used ultrasonic transducer arrays to image a surface opening crack in concrete [10]. However, an individual NDT method is usually incapable of handling all problems for concrete structures. Therefore in 2004, Kohl et al. developed a data fusion technique making use of radar, ultrasonic and impact echo data integrally [11–13]. This method is capable of dealing with many aspects of evaluation work for RC structures, yet the cost may be high.

In 2007, Tong et al. used SAFT to process the response signals of stress waves propagating in a concrete structure and succeeded to create an image of a void defect embedded in the structure

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[14]. In the same time, Sridharana et al. also developed a similar method [15,16]. The depth range of successful detection can be considerably enhanced by using this kind of mechanical impact as a source rather than an ultrasonic or pulse-echo source. Furthermore the required equipments are handy and the cost is comparatively low. In 2010, Tong et al. proposed an improved method with SAFT by introducing the Hilbert–Huang transform (HHT) for higher quality of the resultant images [17].

Most of these researches tried to detect possible defects implied in a concrete structure with one-directional scanning. In such cases the location of a defect may be revealed but the detailed geometry of the defect such as its shape and size and nearby defects cannot be precisely described. Moreover, the interferences of the reflections from the boundaries of structures usually reduce the quality of the processed image for presenting the defect. The initial motivation of this research was to present the detailed geometry of possible defects in concrete structures using multi-directional scanning and SAFT. The practice of applying this technique may be another issue to be discussed.

## 2. Principles of SAFT imaging

When concrete structures are inspected using elastic-wave based SAFT imaging, the resultant image is similar to that obtained using a phase array system. This test is usually performed using only one point-source/point-receiver set each time so that the used apparatus is much simpler than a phase array system. As shown in Fig. 1, a series of impact-and-receive operations is performed on the upper surface of the tested specimen. Let $S_i$ and $R_i$ denote the locations of the source and the receiver, respectively, for the $i$-th impact-and-receive operation. Furthermore, let $T_i(t)$ be the response trace recorded at $R_i$ during this operation. Based on its geometric design, the specimen can be meshed into grids, as shown in Fig. 1. An image intensity $I(m,n)$ can be assigned to each grid based on the following calculation:

$$I(m,n) = \frac{1}{N}\sum_{i=1}^{N} T_i(t_i) \tag{1}$$

$$t_1 = \frac{|\overrightarrow{S_iG}| + |\overrightarrow{GR_i}|}{C_p} \tag{2}$$

where $m$ and $n$ represent the row and column where the grid is located in the mesh, $N$ is the total number of the obtained response traces, and $C_P$ is the propagating velocity of the longitudinal wave. The image intensity $I$ corresponding to each grid is determined by adding the amplitude of each trace on time $t_i$ and then adopting the average value. Finally, a particular brightness on the grayscale specifying each grid according to its image intensity can be displayed on the computer screen. After this image processing procedure, the defects and interfaces in the matrix material can be exposed. In this study, abnormality or discontinuous interfaces with high image intensity were displayed in bright white, whereas a uniform matrix with low image intensity was displayed in deep black.

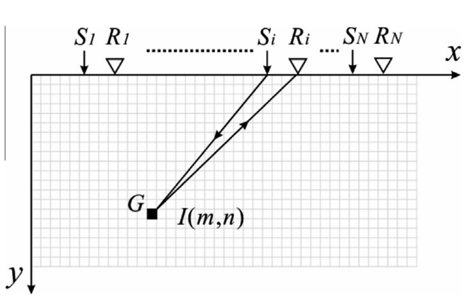


**Fig. 1.** Schematic showing impact-and-receive operations and meshing of specimen for image processing with SAFT.

Because of inconsistencies in the strength of impact at each time, and the contrasting properties of the contact area, the contribution of each signal regarding the intensity of the image was also inconsistent. For reducing the scale of error caused by variances between the levels of energy received from each signal, the maximum amplitude of the first arrival Rayleigh wave was applied as a factor to normalize all of the experimental signals. Thus, a new image intensity $I(m,n)$ could be applied based on the following calculation:

$$\bar{I}(m,n) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{A_i}T_i(t_i) \tag{3}$$

where $A_i$ represents the absolute maximum amplitude in all of the signals. This study attempted to superpose the image intensity of signals emanating from each direction and reveal a new matrix of image intensities that could be used to generate a new SAFT image, as expressed in (4). However, the weighting of each matrix was not equal; hence, each matrix had to be normalized. The image intensity $\bar{I}'$ could be reassigned based on the following calculation:

$$I'(m,n) = \sum_{i=1}^{K}\bar{I}_i(m,n) \tag{4}$$

$$\bar{I}'(m,n) = \frac{1}{K}\sum_{i=1}^{K}\frac{1}{\bar{I}_i}\times\bar{I}_i(m,n) \tag{5}$$

where $K$ is the total number of intensity array of detection element and $\bar{I}_i$ represents the maximum image intensity of the $i$-th image array. However, it was noted that a part of the defect image could possibly be lost when the image intensity was calculated using Eq. (5). This was because the highest signal intensity may have been added to the signal at a lower intensity if it was in the same element position. Thus, the intensity of this element may not have belonged to the largest signal, which could have caused the loss of some information on the defect in the stacking SAFT image. Therefore, this study captured the maximum value that represents the intensity of the element by comparing the value of the element at the same position in each intensity matrix. The new matrix $I''$ could be calculated as follows:

$$I''(m,n)\sum_{m=1}^{M}\sum_{n=1}^{N}\max(\bar{I}_1,\bar{I}_2,\bar{I}_3,\ldots,\bar{I}_k) \tag{6}$$

## 3. Numerical results from using a multi-directional SAFT image

In this study, the Lame constants, $\lambda$, $\mu$, and the mass density used for concrete were $6.890\times10^9\ \mathrm{N/m^2}$, $1.379\times10^{10}\ \mathrm{N/m^2}$, and $2300\ \mathrm{kg/m^3}$, respectively. For rebar, the used values for the corresponding variables were $6.436\times10^9\ \mathrm{N/m^2}$, $8.030\times10^{10}\ \mathrm{N/m^2}$, and $7700\ \mathrm{kg/m^3}$, respectively.

### 3.1. Defective concrete plate with one void defect

First consider a concrete plate with a rectangular void defect. The plane view of this specimen is shown in Fig. 2. To evaluate the feasibility of applying multi-directional signals to establish a SAFT image, a finite difference program for solving 2D plain-stress problems was developed as the numerical tool. To implement the finite difference scheme, the domain in this research, i.e., a concrete plate is meshed with uniformly spaced lines in horizontal and vertical directions to form square grids (or "elements"). The