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Defect detection around rebars in concrete using focused ultrasound and reverse time migration

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ABSTRACT

Experimental and numerical investigations have been performed to assess the feasibility of damage detection around rebars in concrete using focused ultrasound and a Reverse Time Migration (RTM) based subsurface imaging algorithm. Since concrete is heterogeneous, an unfocused ultrasonic field will be randomly scattered by the aggregates, thereby masking information about damage(s). A focused ultrasonic field, on the other hand, increases the possibility of detection of an anomaly due to enhanced amplitude of the incident field in the focal region. Further, the RTM based reconstruction using scattered focused field data is capable of creating clear images of the inspected region of interest. Since scattering of a focused field by a damaged rebar differs qualitatively from that of an undamaged rebar, distinct images of damaged and undamaged situations are obtained in the RTM generated images. This is demonstrated with both numerical and experimental investigations. The total scattered field, acquired on the surface of the concrete medium, is used as input for the RTM algorithm to generate the subsurface image that helps to identify the damage. The proposed technique, therefore, has some advantage since knowledge about the undamaged scenario for the concrete medium is not necessary to assess its integrity.

1. Introduction

Ultrasonic inspection is used for non-destructive evaluation of concrete, typically, as a complementary tool to Ground Penetrating Radar (GPR) [1,2]. The Ground Penetrating Radar is mainly used to detect rebars and metallic tendon ducts in concrete bridge decks. Shifts in the frequency spectrum, relative changes in the amplitude and arrival times of identifiable portions of the scattered GPR waveform are considered as indicators of the rebar integrity and the extent of damage [3–5]. If the scattered field emanating from a defect is less contaminated by clutter noise, the performance of the associated reconstruction algorithm is expected to be good. In the presence of a dense distribution of rebars in a concrete structure, there is strong reflection of the electromagnetic waves which may mask weaker scattering signatures from damage affected regions. Ultrasonic inspection may be useful in such situations since the waves are scattered relatively less by rebars but are extremely sensitive towards the presence of interfaces having strong mismatch in impedances, like cracks and air-voids. In this context, ultrasound can be used as a complementary tool to the GPR modality for assessment of damage in concrete. Besides GPR there are methods based on half-cell potential measurements [6] or usage of embedded piezoelectric sensors for detection of delaminations or material damage in rebars [7,8]. The half-cell potential technique requires access to the exposed end of a rebar which may not be always possible in various structures. Structural health monitoring with embedded sensors may require expensive instrumentation for carrying out a survey. In such situations, surface based ultrasonic inspection provides an inexpensive and convenient alternative which can be applied on existing in-service structures.

One of the common algorithms for imaging with scattered ultrasonic waves is the Synthetic Aperture Focusing Technique (SAFT) [9], also known as Synthetic Aperture Radar (SAR) [10]. Successful imaging of defects, using SAFT in materials like composites and concrete through numerical simulation and experimental investigation has been reported in [11–14]. Recent developments in the field of synthetic aperture imaging of concrete involve the application of 2D arrays [15–18] which employ shear waves for interrogation of the medium. Condition monitoring of tendon ducts using shear wave transducer arrays has been reported in [16,17], wherein the SAFT generated C-scan images of the scattered field are used to identify the embedded artificial defects as steel plate or air-voids. It is also demonstrated that the phase information corresponding to reflected signals can be used to distinguish

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between different types of embedded objects [17]. Commercially available array systems that use the SAFT imaging modality have also been applied for monitoring the integrity of concrete pavements [19–22]. However, SAFT may have limitations with regard to detection of vertical interfaces or objects with steeply inclined boundaries. Moreover there may be artifacts or ghost images in the SAFT generated image due to surface waves, multiple reflections and mode conversions of the wave field originating at interfaces, resulting in wrong conclusions about the scatterer location. Despite these apparent limitations, SAFT still remains the most adopted algorithm in the field of ultrasonic non-destructive evaluation due to faster processing and low data storage requirements.

There exists another subsurface imaging algorithm, popular in the field of geophysics, which is known as the Reverse Time Migration (RTM) technique [23–26]. The physics of the RTM algorithm is based on the principle of Time Reversal of waves investigated extensively by Fink et al. [27–33] and others [34–37]. In physical time reversal, the medium is first excited with ultrasound and the field scattered by an internal object is recorded by a receiver array. The transmitters are then introduced at the receiver locations and the recorded fields are time reversed and fed into the transmitters. The generated ultrasonic field focuses back to the location of the scatterer. In case of multiple scatterers, the field gets focused back on all of the scatterers inside the medium. However, in the presence of a dominant scatterer, the energy is pre-dominantly focused back towards that location.

The RTM algorithm, for the purpose of imaging of a medium, requires high end computational resources with large memory and data storage capacity. These requirements restrict RTM from being used on the fly during inspection operations. Rather, RTM works as a post processing tool for image reconstruction. These reasons have possibly restricted the application of RTM mostly to the oil exploration industry. With advancements in parallel processing of computational resources, the technique has potential for being used in other fields. Application of RTM for imaging of defects with the scattered Lamb wave field has been reported in [38]. The application of this technique towards detection of acoustic emission sources due to crack initiation in concrete media has been reported in [39,40]. A recent application of RTM in the field of non-destructive evaluation is reported in [41], where the authors use synthetic data to image vertical interfaces and circular objects embedded in polyamide, and in concrete media in the presence of small distributed scatterers.

The RTM technique utilizing a full elastic wave propagation algorithm does not have issues with multiple reflections [41] and the mode conversions (compressional to shear wave conversions and vice versa) arising from interaction of elastic waves with interfaces. For this reason, it is expected that the RTM generated image will contain less artifacts in comparison to the SAFT image of the same medium. SAFT performs back propagation using the compressional or the shear wave velocity information, which creates artifacts in case where the scattered field contains mode converted wave field data. This aspect therefore presents an inherent advantage of the RTM algorithm vis-à-vis SAFT.

In this paper, we present results from experimental and numerical investigations on application of the RTM algorithm for evaluation of integrity of rebars embedded in concrete. Subsurface defects in concrete are always undesirable since they affect the strength of concrete and pose a risk of further degradation under adverse loading and environmental conditions. Defects around rebars include partial or complete delamination near the rebar surface due to the imperfect casting condition or cracking under fire or earthquake loads. These defects around the rebars are a matter of utmost concern since they may lead to dramatic decrease in the strength of the member due to increased possibility of slip at the steel–concrete interface. Damage of the material around the rebar due to the rusting of steel under chloride or carbonation ingress may be another cause of the above mentioned defect. The term damage in this paper exclusively refers to the defects discussed in the above context. We use focused ultrasound to assess the condition of rebars since a focused field has a greater probability of detection of a defect existing in the chosen focal region of interest (ROI). The focused field directs more energy towards the chosen ROI and partially circumvents the scattering and attenuation of the ultrasonic field due to interactions with the aggregates and the cement mortar matrix. There have been attempts at focusing of Lamb waves in thin plates towards particular directions using beam forming techniques to magnify the scattered field from damaged regions [42,43]. Beam steering of ultrasound for concrete inspection using phased array technology has been reported in [44–47]. In this paper, we propose a similar concept of focusing compressional waves towards a known rebar location inside the concrete to enhance the possibility of detection of a defect in the vicinity of the rebar. The total field that is received at a receiver array aperture is used as input for the elastic wave based RTM algorithm for generating the subsurface image. To the best of the authors' knowledge, the feasibility of such an approach involving focused ultrasound and a full elastic wave based RTM algorithm has not yet been investigated in the context of non-destructive evaluation of rebar integrity in concrete.

The paper is organized as follows. The next section presents results from numerical simulation of focused ultrasonic wave propagation in concrete using the Finite Difference in the Time Domain (FDTD) technique. The section first provides background on the FDTD simulation scheme for generation of synthetic scattered field data. It is then followed by numerical investigations on the subsurface reconstruction using the RTM based algorithm and the widely applied Zero-Lag Cross-Correlation Imaging Condition [51]. In the subsequent sections, we assess the performance of the proposed technique by presenting results of ultrasonic experiments on an actual concrete medium. The paper ends with a conclusion section and description of future work.

2. Numerical simulations

2.1. FDTD simulation geometry

The goal of FDTD simulations is to assess the proposed methodology using synthetic ultrasonic scattered field data. The simulation medium (Fig. 1) consists of five steel rebars of either 16 or 20 mm diameter in cement concrete. The medium is 400 mm wide and 250 mm deep. The centers of the rebars in the top layer (#1 and #2) are at a depth of 130 mm and the centers of bottom layer of rebars (#3 through #5) are at a depth of 170 mm from top surface. The coarse and fine aggregates have been modeled as a random spatial distribution of elliptical aggregate particles embedded in the cement paste (Fig. 1).

The medium also contains 1% volume fraction of sub millimeter sized air voids. The coarse aggregates have a volume fraction 42% and their nominal maximum size is 20 mm, which is the common practice in concrete construction. The rebar on the top left (#1) and the bottom center (#4) have a delamination (in the form of air wrap) around them of 0.5 mm size, which separates the steel from the surrounding concrete. The other rebars (#2, #3 and #5) are perfectly bonded to the concrete and therefore simulate healthy rebars. The diameters of the rebars in millimeters are shown in Fig. 1, including the delamination around two of the rebars. The material properties of the constituents inside the simulation medium are presented in Table 1.

For carrying out the calculations, an FDTD model has been developed by the authors using the MATLAB platform. The