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Multi sensor data fusion approach for automatic honeycomb detection in concrete

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ABSTRACT

We present a systematic approach for fusion of multi-sensory nondestructive testing data. Our data set consists of impact-echo, ultrasonic pulse echo and ground penetrating radar data collected on a large-scale concrete specimen with built-in honeycombing defects. From each data set, the most significant signatures of honeycombs were extracted in the form of features. We applied two simple data fusion algorithms to the data: Dempster's rule of combination and the Hadamard product. The performance of the fusion rules versus the single-sensor testing was evaluated. The fusion rules exhibit a slight improvement of false alarm rate over the best single sensor.

1. Introduction

Non-destructive testing (NDT) is evolving as an integral part of inspection and quality assurance/quality control (QA/QC) practices in many branches of civil engineering (CE). Some of the common applications of NDT in CE include detection of geometrical boundaries, embedded reinforcement and various defects. Ultrasonic (US), impact-echo (IE), and ground penetrating radar (GPR) testing are some of the most common NDT methods for structural evaluation. These techniques have been greatly developed over the past decade and their applications have reached a certain degree of maturity. Nevertheless, the performance of each testing method is affected by methodological and physical limitations. Therefore, it is often necessary to deploy more than one technique to achieve the desired level of reliability [1,2]. On the other hand, the development of automated NDT systems has facilitated the collection of multi-sensor data of high quality [3–5]. Yet, the individual sensor results are still evaluated independently and often manually. A final common conclusion is made based on the side-by-side comparison of individual evaluations by a specialist. Combining the redundant and complementary information in a multi-sensor dataset using the fusion algorithms is the logical next step of development. An improved reliability in defect detection and characterization is the expected added value of data fusion [6].

This contribution presents a systematic approach for the fusion of multi-sensor data at feature level for the automatic detection of honeycombs in concrete. Our dataset consists of IE, US and GPR data automatically collected on a large-scale concrete specimen. The specimen contains three distinct built-in honeycombing defects [7]. Honeycombs are porous volumes of coarse grain aggregates bonded together by cement. In practice, these defects are formed when the fresh concrete ingredients segregate e.g., due to granular convection effects. The presence of large honeycombs result in a loss of load-bearing capacity, impermeability and density in the affected structural element. Thus, the integrity and serviceability of structures containing honeycombs may be compromised. For example, the weakened cross section could give rise to load eccentricity. Rebar corrosion or mold fungus may result due to an increased susceptibility to moisture and salt ingression. When suspected, reliable detection and accurate localization of these defects are essential in order to take proper repair measures.

Detection and characterization of honeycombs is a challenging inspection task. The challenge lies in their strong variability in size, shape, position, orientation and density. Moreover, unlike voids of the comparable size, honeycombs introduce a gradual and volumetrically distributed change in material properties [8]. Therefore, their direct detection is hardly possible in practice [9,10]. The stated challenges merit a multi-sensor investigation.

This study presents a three-sensor investigation for detection of simulated honeycombs in concrete, including the details of the experimental investigation, data analysis and finally, the fusion of the individual sensor results. We first discuss the pre-processing steps, feature extraction procedure and the selected features in each. We will then introduce the fusion algorithms applied to the extracted features, namely Dempster's rule of combination and an algebraic fusion approach. Finally, the fusion results are presented and evaluated.

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1.1. Objective, scope and novelty of the research

The primary objective of this study is to quantitatively evaluate the effectiveness of several data fusion algorithms, when applied to multi-sensor NDT to detect honeycomb defects in concrete. The dataset consists of IE, US and GPR measurements collected on a concrete specimen with built-in honeycombing defects. The novelty of this work does not lie in deploying multiple sensors for concrete evaluation, but in the synergic combining of their results to obtain more reliable evaluation. A systematic framework for multi-modal NDT data fusion for defect classification is laid out. New analysis procedures are introduced to extract relevant information from each sensor. Finally, the value added of the proposed fusion procedures is quantified.

1.2. Multisensory approach

The underlying concept of multi-sensor defect classification is illustrated in Fig. 1. The signals from various NDT sensors are influenced differently by various defects due to the differences in their underlying physical principles. We define features as the most prominent signatures in the signal induced by the presence of a particular defect. The feature values can be regarded as logical statements that indicate the state of test structure within the limitations of each sensor [11]. We interpret indications obtained from individual sensors to classify the defects. In a complex environment, various defects could have similar influences on the signals and thus similar feature values. This could lead to erroneous or ambiguous interpretations in single-sensor testing systems. In a multi-sensor setting, redundant and complementary feature values from different sensors can be combined and fused to provide a comprehensive and more reliable classification.

The diagram in Fig. 1 is presented for the classification of honeycombing and delamination defects only. However, this basic framework is in principle not limited as such and could be easily extended to include a larger number of defects, sensors and features.

1.3. Experiments and specimen

Measurements were carried out on a reinforced concrete slab with inter alia built-in simulated honeycomb defects. The slab thickness is 30 cm. The concrete cover cv is about 3 cm. The top and bottom reinforcements consist of a wire mesh from 10 mm—diameter construction steel spaced at 15 cm (Q524).

Since it is nearly impossible to intentionally create well-controlled honeycombing during the casting of a test specimen, the honeycombs were pre-manufactured and placed in pre-defined positions before casting of the slab (see Fig. 2 left). The honeycombed volumes were made in a cylindrical formwork using cement paste and coarse grain aggregates. The outer surface was sealed by applying mortar to prevent concrete from penetrating the inner volume of honeycombs during the casting stage. This art of artificial honeycombing manufacturing has been applied at BAM for many years [8]. The cylindrical (diameter (d) = 15 cm, height (h) = 15 cm) honeycombs were arranged in three different orientations in the specimen. The concrete cover for all of them is about 11 cm. The locations of honeycombs as well as the slab reinforcement mesh are shown in Fig. 2 right. The marked 30 cm × 30 cm square at the bottom left corner of the slab is an inclined section with linearly varying thickness created by embedding a polystyrene wedge in concrete.

Data was automatically collected on 1.2 m × 1.26 m area on a predefined square grid using a scanner system developed at BAM [12]. The spatial grid spacing was 2 cm for IE and US, respectively and 0.5 cm for GPR.

1.4. Methodology

The first data analysis step is the extraction of features in each individual dataset. Features mark the most relevant characteristics of signals for the detection of honeycombs. The detection principle for US is already established [13–15]. Similar procedures were developed for IE and GPR data. The data fusion approach and different employed algorithms are explained thereafter.

An Acoustic Control Systems Ltd. A1220 shear wave pulse echo ultrasonic sensor [16] was used for ultrasonic data collection. This sensor has a center frequency of about 50 kHz which is suitable for the inspection of concrete structures. The data was collected using two polarizations with a sampling rate of 1 MHz and a signal length of 1000 samples. The excitation signal was a square wave pulse. Raw data was migrated using pass band filters and the Synthetic Aperture Focusing Technique (SAFT) algorithm [17]. The post-migration amplitudes, arranged in a three-dimensional cube, form the basis for feature extraction.

The IE measurements were carried out with an especial in-house built system. An automated steel hammer of 8 mm diameter was used as the impactor. An Acoustic Control Systems Ltd. A1220 compressional wave ultrasonic sensor [16] of center frequency of about 50 kHz was used as the receiver. The sampling rate was 0.5 MHz. The recorded signal length was 2000 samples.

A GSSI 1.5 GHz antenna was used for GPR data collection here. This is one of the most widely used GPR antennas for the assessment of concrete structures [18,19]. The data was collected using two polarizations. The Raw data was migrated using band-pass filters and Kirchhoff migration [20]. The reflection magnitudes, arranged in a three-dimensional cube, form the basis for feature extraction. The recorded signal length was 512 samples.

2. Feature extraction

IE and US testing techniques use the principles of elastic wave propagation to detect defects [21,22] while GPR testing is based on electromagnetic wave propagation [23]. The porosities in honeycombs are mostly so small that they can neither be resolved nor be regarded as reflectors by any of these techniques (when operating at frequencies suitable for the inspection of concrete). Nevertheless, a concentrated region of higher pore volume noticeably changes the concretes attributes: the overall density is reduced and the concrete matrix is less homogenous. The obvious consequences are slower speed and the higher damping of waves propagating through the defect region. We have taken advantage of both higher attenuation and slower wave propagation for honeycomb detection.

2.1. Feature extraction from ultrasonic data

Although there are very little direct reflections from the honeycombs, the ultrasound signals are affected by honeycombing in other ways. The changes are most visible where the rear wall reflection is expected; in the presence of honeycombs, the back-wall reflection amplitudes are significantly reduced compared to those in no-defect areas. This suggests a significantly higher attenuation of the signal. Moreover, the presence of honeycombs results in a slight decrease in average wave speed and thus a shift in the back-wall reflection on the time axis. In other words, the back-wall at the location of honeycombing appears to be further from the surface (deeper) than it actually is. The wave velocity could be used as a measure of concrete quality (see Fig. 3 left). The distribution of wave velocities across the test area may be considered as a viable US-feature in addition to velocity. An alternative feature has been extracted from our 3D data set by mapping the amplitude of reflections, where the reflections from the back wall are expected (see Fig. 3 right). The honeycombs can be