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Combined use of thermography and ultrasound for the characterization of subsurface cracks in concrete

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ABSTRACT

Corrosion of metal reinforcement in concrete structures leads to cracks extending towards the surface. These cracks do not show any visual sign until they break the surface, exposing the structure to more accelerated deterioration. In order to develop a methodology for subsurface damage characterization, a combination of nondestructive testing (NDT) techniques was applied. Thermography is specialized in subsurface damage identification due to anomalies that inhomogeneities impose on the temperature field. Additionally, ultrasonic Rayleigh waves are constrained near the surface and therefore, are ideal for characterization of near-surface damage. In this study, an infrared camera scans the specimen in order to indicate the position of the crack. Consequently, ultrasonic sensors are placed on the specified part of the surface in order to make a more detailed assessment for the depth of the crack. Although there is no visual sign of damage, Rayleigh waves are influenced in terms of velocity and attenuation. Numerical simulations are also conducted, to propose suitable parameters like frequency for more accurate testing. The combination of the NDT techniques seems promising for real structures assessment.

1. Introduction

The deterioration of civil infrastructure calls for effective methods of monitoring and repair. The maintenance procedure usually employs a combination of techniques [1]. First a global monitoring technique for the general assessment of the structure in a time efficient manner is applied. The results indicate the severity of the condition and localize the specific parts of the structure which require more detailed examination. Consequently, another technique can be applied locally at the specified positions for a more accurate characterization of the damage parameters [2].

Subsurface cracking in concrete structures may occur due to corrosion of reinforcement if environmental agents penetrate into the material [3]. The layer of oxides formed on the bar, applies additional stresses in the concrete matrix, resulting in its cracking. These cracks propagate with the increase of corrosion, as well as due to thermal cycles and external loading (see Fig. 1). However, they are not visible until they break the surface. Therefore, their assessment by visual inspection is not possible until late. When they break the surface they accelerate the deterioration through the direct channel the crack supplies to water penetration in the structure. It is reasonable that an NDT methodology is demanded for the early assessment of the material's condition in order for the engineers to take the proper action, which could be epoxy or cement injection at the specific position in order to seal the crack [4]. In the present case, this is attempted by the combination of thermography, used as a global monitoring tool to indicate the possible areas of subsurface defects and one-sided ultrasonic propagation, parameters of which are influenced mainly by the depth of damage on the specified areas.

The application of infrared thermography in civil engineering is an established nondestructive method for economical, accurate and convenient investigation of the quality of insulation of buildings, heat loss through windows, or "hidden details" like subsurface defects and delaminations [5–8]. The heat rate is influenced by the presence of defects inside the mass of concrete. This influence may be projected to the surface by variations of the temperature distribution. The variation is stronger as the defects are closer to the surface. Cameras collect infrared radiation emitted by the surface, convert it into electrical signals and create a thermal image showing the body's surface temperature distribution. This distribution is influenced by the existence of subsurface inhomogeneities which leave their fingerprint on the surface temperature field.

Concerning elastic waves, their parameters such as wave speed and transmission in general are influenced by the existence of damage [9]. As long as one-sided measurements are concerned, the propagation velocities of longitudinal and Rayleigh waves decrease for damaged material, while the attenuation coefficient increases mainly due to scattering [10]. Elastic waves have been

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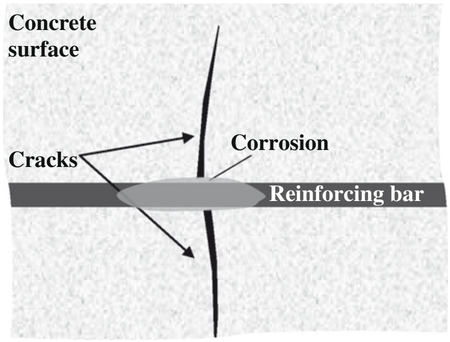

Fig. 1. Development of subsurface cracks by corrosion of rebar.

investigated for the detection of surface and near-surface cracks, showing mainly that their amplitude and frequency is influenced by the existence of damage [11–14]. Therefore, the interaction between subsurface cracks and wave parameters obtained by one-sided measurements are of considerable interest.

In the present study, steel fiber-reinforced concrete prism specimens were subjected to four-point bending. This resulted in visible cracks propagating from the bottom, tensile side to the top. Due to the fiber action, the specimens were not separated in two parts and the crack was halted before reaching the compression side. An infrared camera was used to scan this side of the specimens at the cooling down stage after heating in an oven. The specimens were also examined by one-sided elastic wave measurements by means of resonant acoustic emission sensors in order to estimate the influence of the crack on basic wave parameters. The specific elastic wave problem was also numerically modelled in order to expand to different frequencies and crack geometries and propose suitable experimental parameters for in situ use.

2. Materials

The specimens were made of steel fiber-reinforced concrete (SFRC). Their size was 100 × 100 × 400 mm. The water to cement ratio by mass was 0.5 and the aggregate to cement ratio 5. The maximum aggregate size was 10 mm. The fiber contents were 0.5%, 1% and 1.5% by volume. Additionally, plain concrete specimens were cast. The specimens were tested in four-point bending for fracture toughness determination (ASTM C1609/C 1609M-05) resulting in approximately vertical cracks which propagated from the bottom tensile surface to the top (see Fig. 2a). Fig. 2b shows a typical crack in SFRC specimen. The main crack is accompanied by smaller cracks, as is typical for this kind of material, increasing the fracture process zone. Despite the network of cracks, which can be seen from the side view, there is no visible sign of them from the compression side. More details on the specimens' composition can be seen in another study [15].

3. Ultrasonic measurements

3.1. Experimental setup

The experimental setup for the elastic wave measurements is depicted in Fig. 3. Two sensors were placed on the intact side of the specimen at a distance of 70 mm. The excitation was conducted by pencil lead break which introduces a frequency band up to approximately 200 kHz. The sensors were common acoustic emission transducers (Physical Acoustics, PAC R6), with nominal maximum sensitivity around 60 kHz with very good response up to 150 kHz, and diameter of 15 mm. The sampling frequency of the acquisition board was set to 5 MHz. This kind of ultrasonic set up is commonly used in monitoring of concrete structures [4,10].

Wave velocity was measured by the time delay between the waveforms collected at the different sensors. Typical waveforms recorded on sound material are depicted in Fig. 4a. For pulse velocity determination the first disturbances (wave onsets in Fig. 4a) were used. The onset corresponds to the longitudinal wave which is the fastest type. Rayleigh wave velocity was measured by the strong characteristic peaks (see again Fig. 4a) of the Rayleigh waves which stand higher than the initial longitudinal arrivals due to their higher energy [16]. Fig. 4b shows typical waveforms for the case of a subsurface cracked concrete specimen. The waveform of the 1st receiver is similar to the intact case; however, the waveform recorded by the second waveform is much lower in amplitude and therefore for presentation purposes it is magnified by 80 in the figure. In some cases with severe cracking it was difficult to discriminate the Rayleigh peak. However, this shows that the crack has cut through the whole cross section. The measurements were repeated 20 times by slightly translating and rotating the receivers' array around the crack in order to study also the exper-

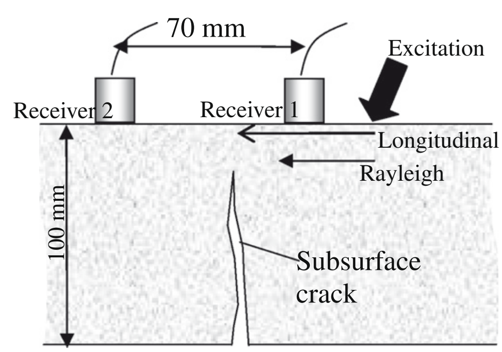

Fig. 3. Experimental setup for one-sided wave measurements.

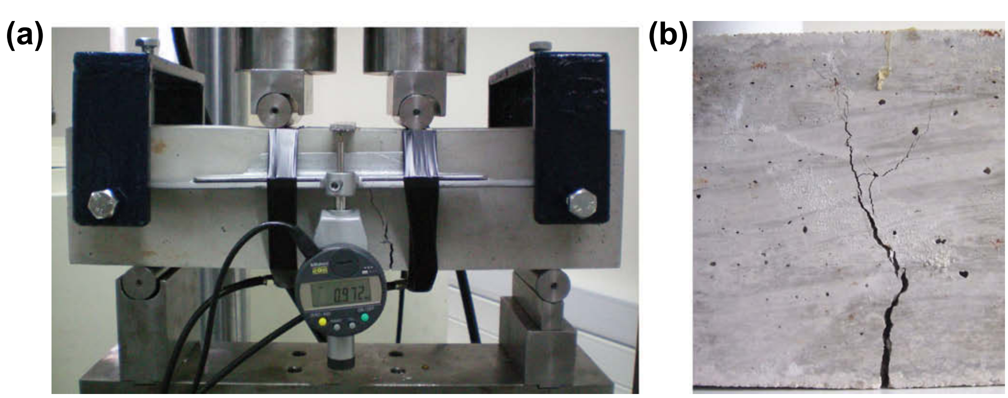

Fig. 2. (a) Experimental setup for four-point bending and (b) typical crack in SFRC.