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Novel concrete crack detection concept by means of shape memory alloy-based fibers

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ABSTRACT: Conventionally, non-continuous techniques are used to detect, locate and quantify structural damages on buildings, bridges or other infrastructure. If a structural damage or failure is detected, continuous monitoring by means of conventional sensors is required until refurbishment or demolition. Moreover, early detection in order to avoid sudden collapse is absolutely necessary. Hence, the search for new nondestructive continuous monitoring methods has become increasingly important in recent years. For this purpose, functional materials can pave the way to novel crack detection possibilities. Among them, thermal shape memory alloys (TSMAs) are potential candidates, due to their advantageous mechanical properties.
This paper reports a novel approach for a structural health monitoring system in concrete structures by means of radio frequency network analysis for crack detection as well as localization. Initial investigations were performed using glass fiber reinforced concrete tensile samples with embedded TSMA fibers. At certain crack opening widths, transmission and reflection were measured in frequency domain. The formation of cracks led to a measurably changed propagation behavior of the electromagnetic wave, showing that information about spatial position and geometry of cracks can be determined.

1 INTRODUCTION

In order to maintain and preserve civil structures, it is necessary to continuously assess their condition. Since new buildings become ever more complex and are crafted for lifespans of many decades, continuous recording of data obtained from the inside of a structure has become crucial for understanding and predicting a buildings' structural performance and remaining life.

Hence, structural health monitoring (SHM) has become a growing field of research, in particular methods for early crack detection (Yao et al. 2014 and Song et al. 2006). Traditionally, the most widely used monitoring systems for crack detection are electrical resistance strain gages (McCarter et al. 2001), piezoelectric ceramics (Kong et al. 2016) and optical fiber sensors (Li et al. 2004, 2007 and Barrias et al. 2016). SHM-based approaches for non-destructive crack localization currently use automatic digital imaging (Sinha et al. 2006, Hampel et a. 2009 and

Barazzetti et al. 2009), radio frequency transmission (Grosse 2013 and Nair et al. 2010) and ultrasound techniques (Wolf et al. 2015), which are instrumented monitoring methods based on integrated sensors.

However, the precise localization of cracks is still a very complex and expensive procedure. All sensing methods mentioned above are still limited when it comes to scalable application in construction. Most SHM systems for crack detection suffer from low sensitivity, poor performance in extreme weather conditions, sophisticated installation procedures, costly maintenance, low local coverage, and temporal limitation of monitoring. Furthermore, there is still no applicable and durable method available on the market that combines continuous, long-term early crack detection, spatially resolved crack localization and width measurement.
The aim of this study is to develop a novel concept for crack detection that addresses these issues. It includes methods for robust and reliable detection as well as location of critical cracks in concrete structures, e.g., in bridges. Thus, critical parts of prone-to-crack infrastructure can be monitored continuously and be targeted with safety precautions or repair measures when structural damages occur. Moreover, crack dimensions, such as crack widths and depth, shall be determined. These goals shall be realized by means of nickel-titanium-based (NiTi) shape memory alloy fibers, embedded over the entire length of a structure. With a tailor-made measuring technique, the targeted system will provide a permanent and non-destructive characterization of the structural condition.

2. THERMAL SHAPE MEMORY ALLOYS

Nowadays, advanced functional materials play a steadily growing role in many technological fields in our modern society. They are capable to adapt their properties according to external stimuli and thus enable the development of novel applications.

Among these materials, thermal shape memory alloys (TSMAs) exhibit a large reversible elongation, which relies on the pseudoelastic effect. NiTi-based TSMAs make sensors feasible with up to 8 % recoverable strain, 40% elongation and gauge factors higher than 5 (Maeder et al. 2017). In contrast, alternate used sensors for structural crack monitoring - like fiber Bragg grating strain sensors - possess factors of less than 1 (Juelich et al. 2013), or conventional strain gages possess gauge factors around 2. The high performance of the TSMA based sensors relies on the combination of the pseudoelastic and piezoresistive effects. In a certain temperature range, this is driven by a reversible stress-induced solid-state phase transformation between austenite and detwinned martensite (Otsuka et al. 1986). Diffusionless transition (volume change is negligible) is followed by a shear lattice distortion, which leads to a macroscopically remarkable “elastic” deformation. Hence, TSMAs allow pseudoelastic and thus reversible strains up to 70 mm / m. By contrast, conventional strain gages can only reproduce strains of approx. 3 mm / m reversibly. In addition, NiTi-based TSMAs also have a very good corrosion and alkali resistance (Janke et al. 2005), which make them a promising candidate for sensing applications in concrete structures. Based on this background, a measuring concept exploiting the pseudoelasticity is designed.

3. MEASURING METHOD

In order to implement a strategy for continuous early crack detection and spatially resolved characterization, the measuring approach of AC radio frequency network analysis for crack occurrence detection and localization is investigated.

High-frequency AC techniques are potential candidates for an accurate monitoring of local crack initiation and propagation. In radio-frequency (RF) engineering, electrical network analysis is a well-established method for characterizing electronic components and evaluating the performance of electric circuits or networks (Seiler et al. 2014 and Fraedrich et al. 2013). Characterization and localization of faults, inclusions (e.g., reinforcement bars) and cavities inside concrete is already state-of-the-art as a “classic” RADAR application (Metesco datasheet 2017 and Hilti PS 1000 X-Scan System 2018), where a signal is emitted into a medium using an antenna, propagates through it, is reflected or diffracted at some object or boundary in its path, and is finally received by the same (or another) antenna (Baur 1985, Balanis 2008 and 2012). However, this approach does not allow continuous monitoring, as it cannot be sensibly embedded into the structure to be monitored.

For the TSMA-based SHM approach presented in this paper, SMA fibers will be placed in concrete structures. These can be arranged to form a Lecher type RF transmission line (Zinke et al. 2000 and Pozar 2011), thus forming an electrical network. A signal will propagate along this transmission line, using the concrete matrix as its background medium. Fractures and cracks, being “disturbances” in the background medium, will cause reflections of the signal which are not present in a homogeneous “undisturbed” sample (i.e., a “perfect” transmission line). In order to find the location of these faults, a broadband pulse signal is transmitted into the line, and the reflected “echo” signal is measured and evaluated for reflection peaks. The location of the disturbance can be calculated, given the speed of light of the propagation medium is known. This technology is known as “time domain reflectometry”. It is used for wire-bound fault detection and other applications for quite some time (O´Connor et al. 1994). The proposed system, in contrast to the traditional method, will work in frequency domain, over a broad bandwidth. The time domain signal can be computed from the measured frequency signal using Fourier transformation. It can provide valuable information about location and geometry of structural strain discontinuities along the embedded TSMA sensors.

4. EXPERIMENTAL PART

In order to investigate the feasibility of this approach, initial tensile tests were performed using electrically non-conductive glass textile reinforced concrete samples with embedded TSMA wires. The tensile sample dimensions were 400 x 100 x 16 mm (Figure 1). Fine grain cement, conforming to the requirements of German Standard DIN EN 197-1 as type CEM III/A 52.5 N, was used as binder material. The composition of the binder matrix is summarized in Table 1. Commercial straight annealed TSMA fibers made of Ti-55,9 %Ni with a nominal diameter of 150 µm provided by Memry (SAES Getters) were used. Their transformations temperatures A_s, A_f, M_s and M_f were -30 °C, 10 °C, -83 °C and -120 °C, respectively. All tests were performed within the pseudoelastic temperature range.

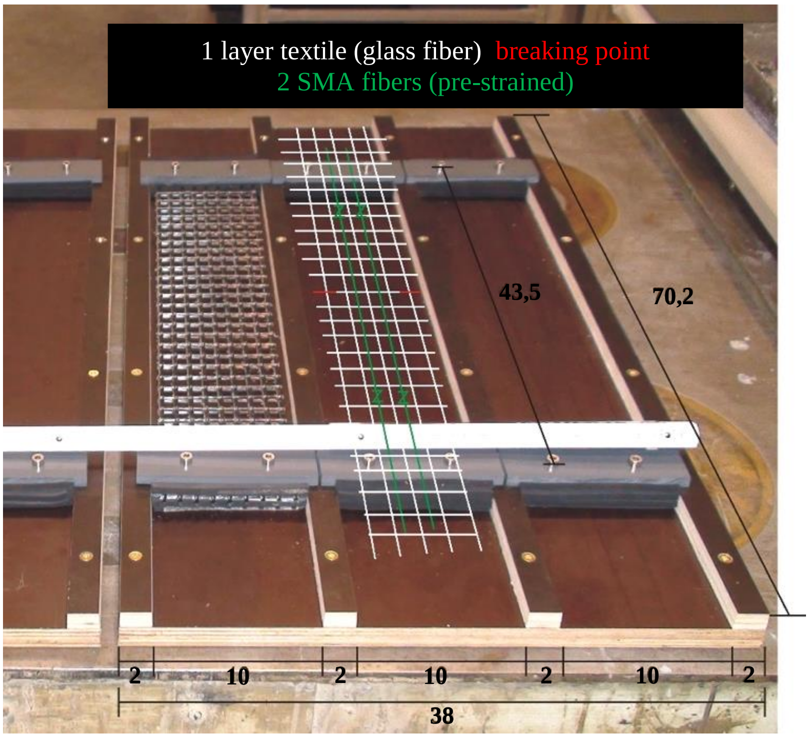

Figure 1: Fabrication of textile reinforced concrete samples with dimensions of 400 x 100 x 16 mm

Table 1: Composition of binder matrix

Material	Supplier		
C³-Nanodur CEMIII	(Dyckerhoff)	[g]	559.3
Quartz powder M500		[g]	142.4
Quartz powder M4		[g]	264.4
Sand BCS 413	(Amm. 0.06-0.2)	[g]	325.4
Sand 0/1	(Ott)	[g]	783.0
VP 150624-01	(MC Bauchemie)	[g]	7.1
Water	(w/c = 0.4)	[g]	223.7

In each sample, a pair of parallel TSMA fibers (both pre-strained at approximately 1,5 %) forming a twin-lead (Zinke et al. 2000) were embedded, as shown schematically in Figure 2. The TSMA fibers were connected to a vector network analyzer (VNA), which transmits an RF signal into the transmission line, and records the received transmitted and reflected signals on both ends.

Small notches were cut in the middle of the textiles in order to create a predetermined breaking point. Initial measurements were performed in order to characterize propagation through the material (Figure 3). Then, the samples were mounted in a testing machine (Instron 8501, Darmstadt, Germany) for performing step-wise tension tests. The transmission and reflection through the TSMA fibers were measured in frequency domain, from 30 MHz to 8.5 GHz, with a Keysight (formerly Agilent) Fieldfox Handheld Microwave Analyzer N9918A. The recorded S-parameter data were transformed to time domain in-device.

Force-controlled tensile tests were carried out after 28 days in order to obtain different cracks states. This allowed a stepwise measurement of the crack development with the VNA.

Figure 2: Schematic diagram of measurement setup

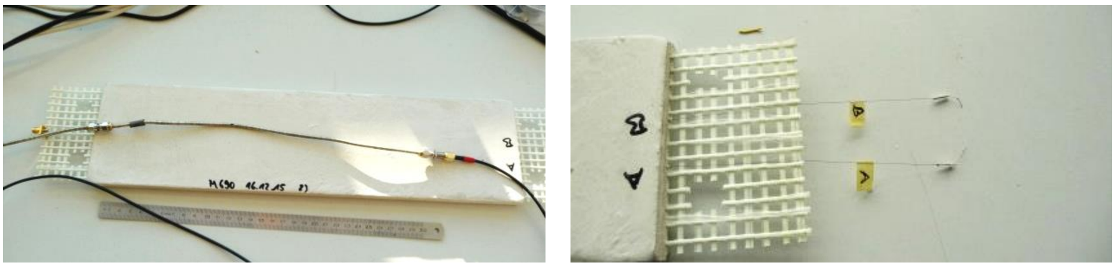

Figure 3: (a) Measurement setup for comparison with a coaxial line, (b) open termination of the twin-lead through the concrete sample

5. RESULTS

In order to validate the measurement concept, the reflected signal strength (S-parameter S11) of the initial tests is plotted (Figure 4). Transformation to time domain was performed in-device, with distances computed assuming free space (i.e., relative permittivity ε_r=1). The distance was set to zero where the first peak occurred. Here the electromagnetic wave encounters the transition from coaxial cable to twin-lead (concrete sample), or the coaxial connector (coax line). It can be seen that the reflection at the insertion point of the concrete sample is very high, at -4 dB (i.e., ≈ 40% of the power is reflected at this interface). The coaxial connector performs much better with ca. -40 dB reflected power (≈ 0.01%). For the coax line, the open end is very well visible, with -21 dB at ~470 mm. The propagation speed through the coaxial cable is 2/3 of the speed of light in vacuum, so the location is nearly correct. The coax line shows no further significant reflections.

In contrast, the concrete sample shows a second discernible reflection just after the transmission line change at about 60 to 70 mm. This is most likely due to the transition from free space to concrete. The strong reflections around 650 to 750 mm and from 850 to 950 mm represent the end of the concrete sample. The setup - as shown in Figure 3 - with an open end of the transmission line in free space, would lead to the expectation of a double reflection like for the beginning of the setup. However, either the glass fiber reinforcement or an inadequate matching at both insertion and termination seems to cause several further reflections, probably including multiple reflections, which hinder an interpretation in more detail. The greater apparent length of the twin-lead transmission line embedded in concrete compared to the coaxial line can be attributed to the propagation through the concrete itself, as concrete has a higher relative permittivity ε_r than free space, and therefore a lower speed of light inside the medium.

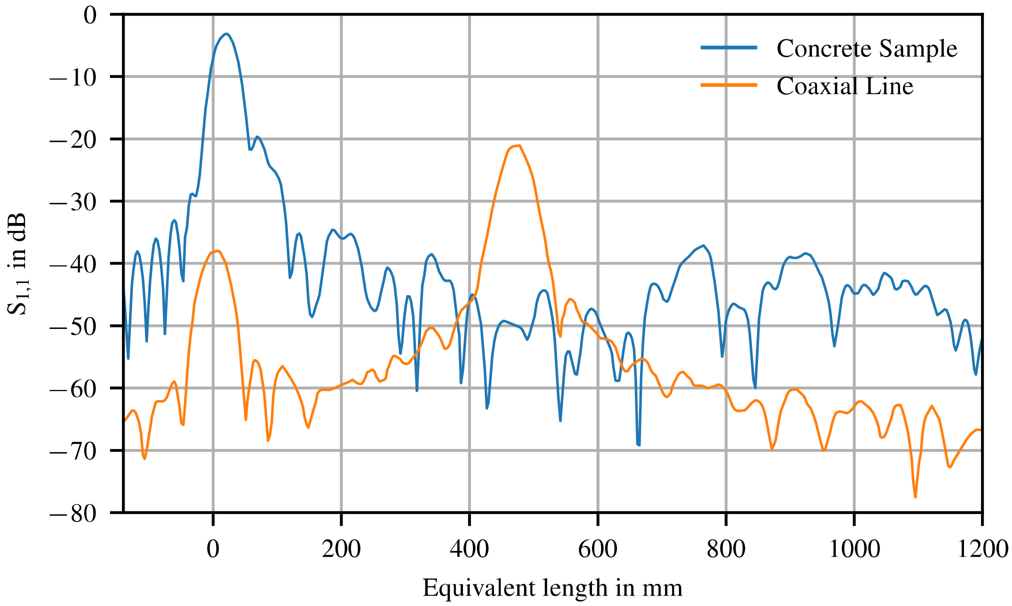

Figure 4: Reflected signal concrete vs. coaxial line

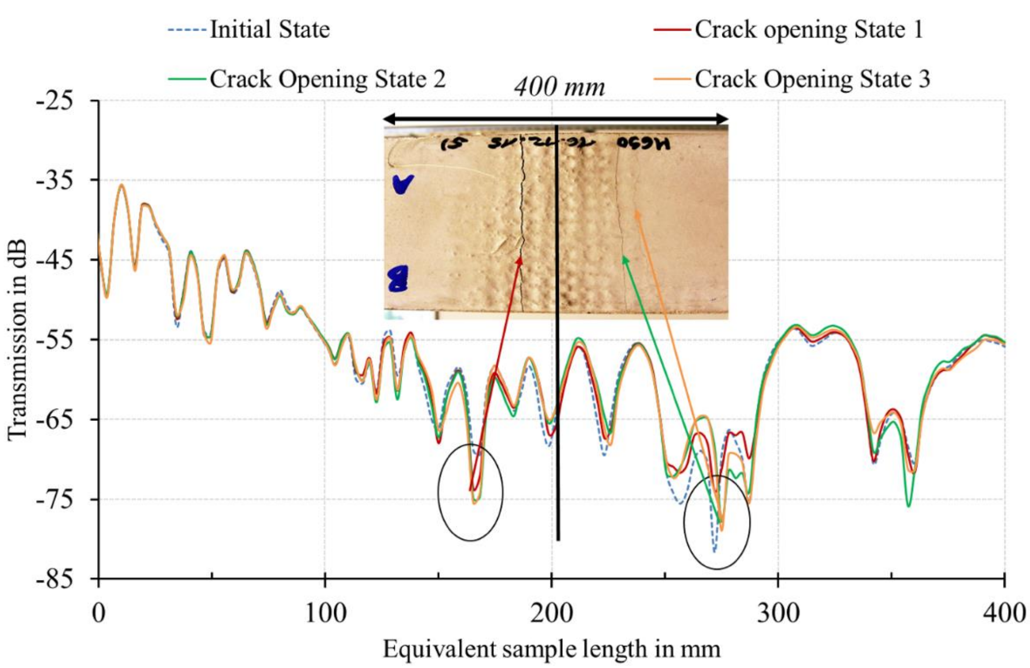

Figure 5: Transmitted signal strength at different stages during tensile tests

Figure 5 shows the transmitted signals (S-parameter S21) transformed into time domain for the initial uncracked sample (blue dashed line) and the different crack opening states. The distances were computed to match the beginning and the end of the sample to correlate the observed signal changes with the occurring crack positions during tensile tests.

It can be seen that the formed cracks cause a pronounced change in the transmitted power (see highlighted peaks) at particular distances. The first visible crack occurred at ~165 mm sample length (red), which is related to a difference in transmitted power of ~5 dB. With further increasing strain, two more cracks opened between 250 mm and 300 mm. This is again connected to a measurable change in wave propagation, as seen in the shifted peaks of the green and orange curves.

This demonstrates that, in principle, the crack location of can be determined within the investigated sample length. However, a full interpretation is complicated due to insufficient matching of insertion point and multiple reflections, potentially caused by the used glass fiber reinforcement.

6. CONCLUSION

In this paper a novel concept for continuous early crack detection and spatially resolved characterization based on structural embedded TSMA sensors combined with a tailor-made AC radio frequency measuring technique has been presented. The results of the initial investigations show the potential of the network analysis measuring technique as well as their continuous monitoring along a defined measuring line in structural concrete construction. It can be stated that the measurement concept works in principle. However, several issues need to be addressed. Based on the above findings, a larger amount of energy is necessary in order to penetrate into the measurement object, thus matching must be improved significantly. An insertion matching better than -10 dB is needed. For this purpose, the relative permittivity of the concrete needs to be determined. Also, as a twin-lead is a symmetrical line but coaxial line is not, a balanced-to-unbalanced converter ("balun") is necessary. For further exploratory measurements, it might be useful to work with larger concrete specimen instead of thin-walled samples, as the latter seem to cause spurious multiple reflections which deteriorate signal quality. These proposals will be investigated in near future.

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