Cement and Concrete Composites 80 (2017) 55–63

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Ultrasonic broadband signals monitoring of glass-fiber reinforced cement (GRC) bending tests

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ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
23 December 2016
Accepted 19 February 2017
Available online 3 March 2017

Keywords:
Glass fibres
Process monitoring
Reinforced cement/plaster
Ultrasonics
Mechanical testing

ABSTRACT

In this study, complete ultrasonic monitoring of Glass-fiber Reinforced Cement plates under bending tests was addressed. In this kind of experiment, the mechanical properties of the specimen continuously change during the test, thus, the acquisition time of the ultrasonic signals is a critical variable. In order to overcome this drawback, a new ultrasonic procedure based on broadband signals (chirp) has been applied. Following this line of thought, the analysed ultrasonic parameters have been split into the parameters that only depend on time, and those that depend on both time and frequency. In particular, the frequency dependent attenuation parameter allows characterizing the evolution of the plate being damaged over a wide frequency range and significantly detecting the main two events happening during the experiment: the first crack and the maximum stress point. In short, this paper demonstrates the suitability of ultrasonic broadband signals for characterizing fiber-reinforced cementitious composites under bending stress.

1. Introduction

Glass-fiber reinforced cement (GRC) is a composite made of Portland cement mortar with a low water/cement (w/c) ratio with a high percentage of paste (water + cement) in relation to the aggregate. The addition of a high proportion of alkali resistant (AR) glass fibers to the mortar matrix (3%–5% by weight of mortar) improves the mechanical properties of the composite, particularly its toughness, flexural strength, and ductility. This composite has an important role in non-steel reinforced pre-cast concrete elements, such as sheets, panels and other slim shapes usually employed in building engineering and architecture, as well as in cast-in-situ sprayed-on surfaces [1,2].

Recently, non-destructive testing (NDT) applied to concrete have been investigated, especially ultrasonics and acoustic spectroscopy, in order to obtain parameters related to the physical and mechanical properties of the material and its durability [3]. Some experimental studies have demonstrated that wave parameters such as the ultrasonic pulse velocity of P-waves are suitable for predicting the dynamic elastic modulus of the concrete, and that the velocity of the S-waves can predict the dynamic shear modulus. These parameters are proportional to the elastic and shear moduli of concrete and also to its compressive strength [4,5]. Other studies based on ultrasound propagation indicate that wave attenuation should be measured for various frequencies, in order to characterise cement-based materials, determining their microstructure, porosity, and other characteristics in both the hardened [6–9] and fresh states [10] and also, ultrasonic guided waves based techniques for monitoring interfaces and discontinuities inside concrete [11,12].

Some studies of construction material tests by ultrasound monitoring have been reported in the literature. Many of them are related to research on metallic specimens because this type of material is used in other engineering fields. However, recent studies of bending tests of reinforced concrete slabs, using ultrasonic monitoring, have been carried out successfully [13,14]. The first approach was recently published by the authors, in which the monitoring of GRC plates under a four point bending test using an ultrasonic pulse with a fixed frequency was carried out. Thus, the P-wave velocity, attenuation, energy and non-linear parameters were obtained [15]. Monitoring mechanical tests with non-destructive techniques provides a wealth of information about the material under study, allowing the prediction of its behaviour. Ultrasonic waves could be appropriate for following the changes during the

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http://dx.doi.org/10.1016/j.cemconcomp.2017.02.009
0958-9465/

mechanical test. GRC plates change their internal structure because micro-cracks develop during the bending test. In these conditions, different ultrasonic frequencies are needed to cover all the changes in the specimen. The disadvantage of this kind of test is the fact that the mechanical properties of the GRC plates change quickly during the test, and it is difficult to inject various signals with different frequencies to cover a wide spectrum. To solve this problem, the authors have also recently published a study of the suitability of broadband signals, comparing different methods and signals to obtain a reliable method to acquire the information of a wide bandwidth with one single signal (chirp) [16]. This procedure permits monitoring a huge range of situations where the test-time has critical effects. The aim of this paper is to apply new ultrasonic acquisition techniques to support the previous results and provide new information about the GRC plates under stress, making use of the attenuation and non-linear ultrasonic parameters in the time and frequency domain.

The remainder of this paper is structured as follows. Section 2 describes the materials and specimens used in this study. It also presents the test layout, composed of the ultrasonic equipment and the mechanical test machine, as well as the ultrasonic parameters extracted from the signals during the experiments. In Section 3, the results are presented, correlating the ultrasonic parameters with mechanical curves. Finally, in Section 4, the conclusions are summarized.

2. Experimental

2.1. Materials and specimens

In this experiment, the specimen dimensions for the bending test were 325 × 50 × 20 mm. The specimens were cut from a 400 × 400 × 20 mm mother plate, obtaining five plates for the tests. Table 1 shows the proportions and information about the raw materials used to fabricate the GRC mother plate. The specimens were made according to the BS EN 1170-5 standard [17].

2.2. Experimental layout

An ultrasonic through-transmission setup was selected due to its penetration capability and accuracy for velocity and attenuation estimation [6,18–20]. The transducers used for transmission and reception were K1SC (General Electric). Both are broadband transducers with a bandwidth centered at 1 MHz. Universal testing machine (Instron model 3382) was used for the four point bending test. The distance between the supports was 295 mm for the passive supports and 98 mm for the active ones. The displacement of the actuator was constant during the test (0.6 mm/min). The transmitter transducer was excited directly by a programmable signal generator (Agilent 33120A).

Table 1
Used dosage for one GRC plate specimen.

Material	Type	Weight [g]
Cement	CEM I 52.5 R	7260
Water	–	2541
Sand	Silica sand 0/2	4864
Superplasticizer	Polycarboxylate ether	14
Fiber	Glass AR 12 mm length	294

In order to do a broadband analysis, the transmitted signal was a swept-frequency signal (chirp). The use of chirp signals enables estimating any parameter in a wide frequency range with a single measurement by applying the proper signal processing. The mathematical expression of the transmitted linear chirp signal is

$$s_{tx}(t) = A_{tx}\cos\left(2\pi f_0 t + \pi\Delta_{f_{max}} t^2\right) rect\left(\frac{t-\frac{T_w}{2}}{T_w}\right) \quad (1)$$

$$\Delta_{f_{max}} = \frac{f_{max}-f_0}{T_w} \quad (2)$$

where A_{tx} is the amplitude of the signal, f_0 is the fundamental frequency, $rect(\cdot)$ is the rectangular function, T_w is the active time of the signal, and $\Delta_{f_{max}}$ controls the maximum frequency ($f_{max} = f_0 + T_w\Delta_{f_{max}}$) which is reached at T_w seconds (Eq. (2)). The selected parameters for the transmitted chirp signal are $A_{tx} = 10$ V, $T_w = 10\ \mu$ s and the frequency range varies from 200 to 1000 kHz. The experiment was monitored by injecting chirp signals with a period (T) equal to 0.5 s. Fig. 1 shows a time line of the test, where three signals are represented: a signal of synchronization between events (Sync.), the transmitted (Tx) and received (Rx) signals, as well as some of the variables used in the mathematical analysis.

The reception transducer was connected to a linear 40 dB pre-amplifier (Panametrics 5600B). The received and amplified ultrasonic signal was captured by a digital oscilloscope (Tektronix DPO3014) with a sampling frequency of 25 MHz. Finally, a laptop was used to control the signal generator and to store the digitized signals.

The experimental layout of the mechanical test is shown in Fig. 2. The plate rests on the passive supports and four metallic angles were attached to the plate in the positions shown. These elements serve to hold the elastic bands which keep constant the pressure between the faces of the transducers and the specimen. A similar system was presented in Ref. [21], yielding consistent results and suitable performance, where the rubber bands kept the appropriate pressure between the transducers and specimen. Pure vaseline was used to ensure an appropriate coupling between the transducers and the faces of the specimen.

2.3. Ultrasonic parameters

Using broadband signals in the analysis allows computing some ultrasound parameters which not only vary in the time domain (during the test) but also in the frequency domain. In order to

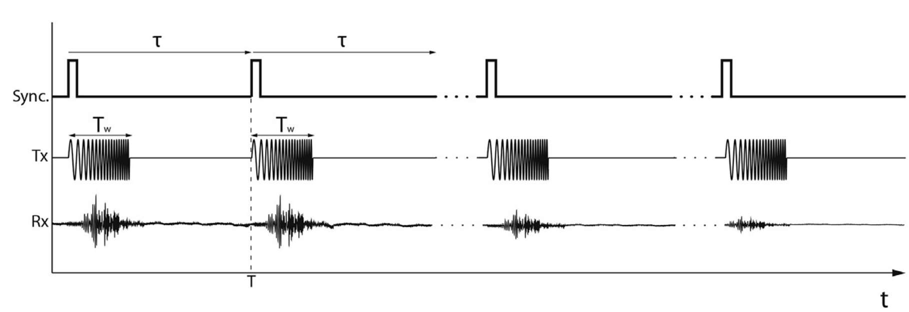

Fig. 1. Time line of the test where three signals are represented: A synchronization signal between events (Sync.), and the transmitted (Tx) and received (Rx) signals, as well as some of the variables used in the mathematical analysis (τ, T and T_w).