Diagnostics of Damages in Reinforced Concrete by the Parameters of Electric Response to Mechanical Impact

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Abstract. A method for non-destructive testing of reinforced concrete based on the phenomenon of mechano-electric transformations is proposed in this work. The procedure for assessing damage in concrete is based on the measurement of an electric response to a weak elastic impact. It was found that the moments of crack formation and growth during bending are accompanied by a significant decrease in the correlation coefficient of the electric responses spectra and by a stepwise change in spectrum shift (at frequency domain) at which the maximum correlation coefficient is observed. It was determined that the increase of energy attenuation coefficient of the electric response can serve as a forerunner of a catastrophic destruction in concrete. The diagnostic criteria proposed in this work can be used for monitoring the damage processes in reinforced concrete under bending conditions.

1. Introduction

At this time, steel reinforced concrete still has a very wide application in building trade and this is one of the main materials used in the construction of large-sized structures. Firstly, this is related to a comparative cheapness and durability. In addition, there is a significant number of constructions that are operated for a long time and the problem of assessing their current status has a high importance. Structures made of reinforced concrete are often used in bending conditions. Therefore, the behaviour of concrete beams under bending conditions is widely studied in the literature. Deformations and stresses in concrete beams are measured, models of flexural cracks are studied, load-deformation behaviour and crack formation processes under bending conditions are investigated [1–2].

Cracks are formed and developed in concrete during a long-term operation under the static and dynamic mechanical stresses. Consequentially, the cracks lead to an unsuspected destruction of the structure. To extend the life of concrete structures and ensure their safe operation, it is necessary to have reliable information about the formation and development of cracks. The information obtained may allow timely implementation of repair and recovery measures or making a decision on the reconstruction of the engineering structure. The problem of monitoring crack formation processes in concrete items and structures is very urgent.

Methods based on acoustic and electric emission [3–11], contact and contactless ultrasonic testing [12–19], impact-echo methods [20–22], acoustic and electric tomography methods [23–25] and other methods [26–27] are used for determining damages in concrete. One of these methods is the method for concrete monitoring by the parameters of electric response to a pulsed mechanical impact [28–30].

The principle of the method is that the object under research is subjected to an elastic mechanical impact. As a result of the impact, acoustic waves start to propagate in the concrete sample. Upon the impact on the surface of a three-dimensional sample, a longitudinal wave propagates into the sample along a hemispherical wavefront and is reflected from the six outer boundaries of the sample. The spherical wave reflection from the side surfaces leads to the formation of waves propagating at different angles in the sample. As a result, a complex wave pattern is formed in the sample, which is determined by the geometry of the sample, its elastic characteristics and the duration of the impact (Figure 1a).

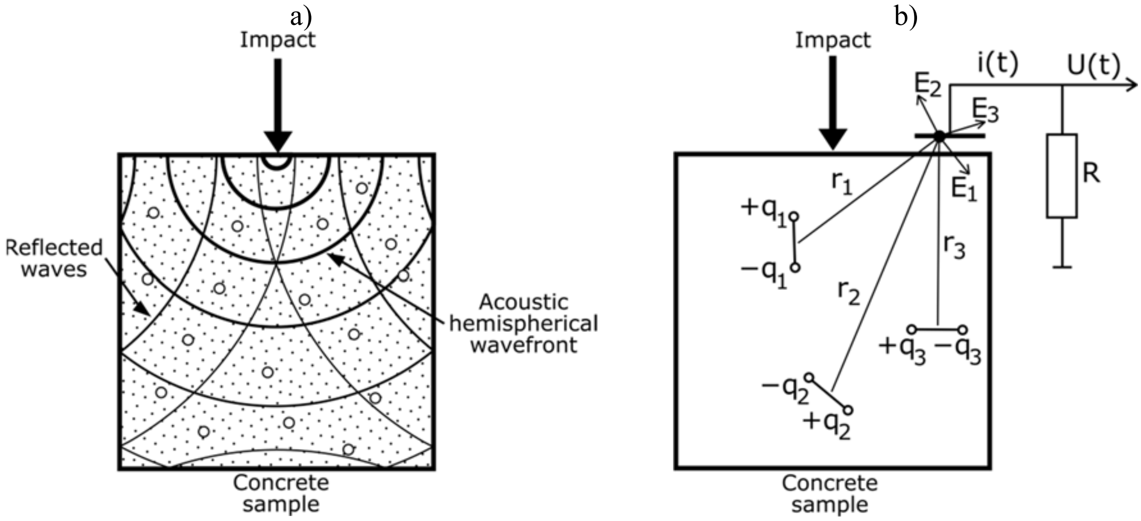

Figure 1. Illustration of mechano-electric transformations method

An alternating electric field arises under the influence of mechanical stresses caused by acoustic waves. The electric field is a result of the deformation and displacement of the double electric layers located at the boundaries of the components in concrete by the elastic wave and the polarization of a piezoelectric quartz contained in sand and gravel [28]. The conducted studies have established that piezoelectric inclusions play a decisive role in mechano-electric transformations in concrete [29]. Piezoelectric inclusions are deformed by mechanical stresses caused by elastic waves in the area of their location. The total electric field at the location of the receiving sensor is vector addition product of the fields from each source.

$$E = E_1 + E_2 + E_3 + \cdots + E_N \quad (1)$$

where N is number of piezoelectric source.

The electric measuring receiver is located in the immediate proximity of the sample and is in the area of the electric field (Figure 1b). Therefore, the parameters of the electric response are related to the characteristics of elastic waves and reliably reflect the processes of their interaction with internal structural inhomogeneities and defects. The main advantage of the method proposed in the work is that the electric response is sensitive to waves propagating in all directions in the sample. It is related to the fact that the electric axes of piezoelectric inclusions have different directions. As a result, the proposed method is sensitive to defects with different orientation and configuration.

The aim of the research presented in this paper was to study the changes of patterns in the parameters of electric response to mechanical impact of reinforced concrete beams at bending process and diagnostic criteria searching for assessing their fracture dynamics.

2. Methods of experimental research

Reinforced concrete beams 100x100x400 mm in size containing a reinforcing cage were produced for the tests. The reinforcing cage consisted of two steel reinforcing bars with diameters of 6 mm and 8 mm with a length of 400 mm, which were interconnected by two short bars. The steel reinforcing bar with the periodic profile was used for producing the reinforcing cage. The concrete samples have been produced in accordance with the Russian technical standard GOST 7473-2010. The cement/sand/coarse aggregate ratio was 1:2:4, the maximum aggregate size was 20 mm, and the water-to-cement ratio was 0.5.

The research was carried out using the laboratory hardware and a software complex. The complex consisted of an external measuring probe, power supply, I/O board and a laptop. The remote probe is a metal cup containing a differential electric sensor and an electromechanical impact device. An electromagnet has been used as an impact device. A capacitive differential sensor has been used to register electric signals, allowing for significant increase of the signal-to-noise ratio and for measuring the electric signal without resorting to the use of shielding systems. The measuring procedure is described in the article of authors Fursa et al. [29] in more detail. Registering, saving, and processing the electric responses has been done via custom software developed by the authors in the LabVIEW programming environment and the Origin application.

The IP-500 computerized press was used in the four-point bending test. The load was applied at a constant rate of 0.05 kN/s. The weak mechanical impact of the sample was produced and the electric response to this impact was measured periodically during mechanical loading. For this purpose, the measuring probe was attached to the side surface of the sample with rubber bands. The frequency of analog-to-digital conversion of the electric response was 100 kHz. The mechanical impacts and registration of electric responses were performed every 5 – 10 seconds.

3. Experimental results and their discussion

According to the method described above, the bending tests of reinforced concrete beams were carried out. Figure 2 shows a typical load-deformation curve obtained by loading a reinforced concrete beam under a four-point bending condition.

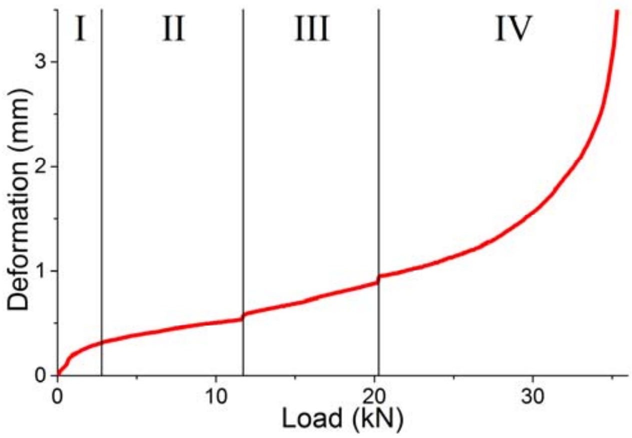

Figure 2. Load-deformation curve obtained by bending of a 100x100x400 mm reinforced concrete beam

As seen from Figure 2, the load-deformation curve has 4 distinctive stages: I – nonlinear deformation, which is associated with the compaction of a weaker surface layer of concrete in contact areas with the lower and upper support blocks; II – the stage of elastic deformation; III – the appearance of cracks in the lower stretched layer of concrete; IV – the stage of destruction of the compressed area of the beam. At loads of 12 kN and 20 kN on the load-deformation curve, there are areas of increasing deformation without changing the load associated with the occurrence of cracks. Later, when analysing the parameters of the electric response, cracks were overlayed on the load-deformation curve in order to bind these parameters to a particular stage of the stress-strain state under bending conditions.

The appearance and development of cracks in reinforced concrete led to a change in the characteristics of acoustic excitation, and consequently, to a change in the parameters of the electric response to this excitation. Scattering of elastic waves upon cracks reflects the process of attenuation with time. Time-frequency analysis as described in [18] was used to determine the energy attenuation coefficient of the signals registered from concrete samples as affected by the magnitude of the external load. Figure 3 shows the dependence of the energy attenuation coefficient of electric responses on the external loading during the reinforced concrete beam bending.

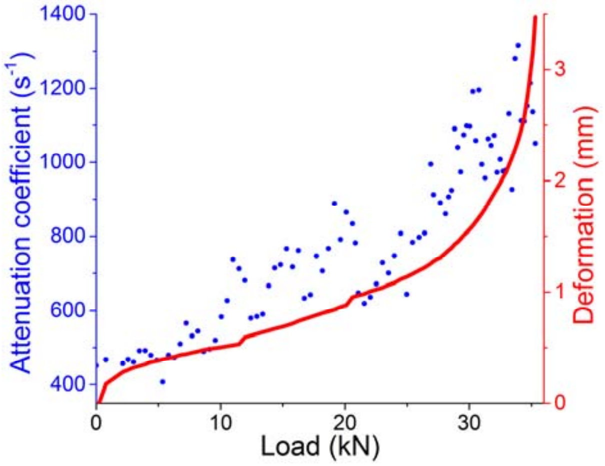

Figure 3. Changing in the energy attenuation coefficient of the electric responses during the bending of a reinforced concrete beam with a size of 100x100x400 mm

As seen from Figure 3, the catastrophic destruction of the reinforced concrete beam occurs with an increase in the energy attenuation coefficient by 2 – 2.5 times. Consequently, the energy attenuation coefficient of the electric responses can be used as a diagnostic parameter, which allows the prediction of coming destruction in reinforced concrete beam. When interacting with the defects, acoustic waves are reflected from cracks and spread around. Multiple passing of acoustic excitation through the defective sample leads to the formation of oscillations with different periods. The spectral characteristic of the signal monitors the presence of the oscillations having different periods. Interpretation of the measured signals in the frequency domain was performed using the power spectral density (Figure 4).

As seen from Figure 4, a significant transformation of electric responses spectra occurred during the bending of reinforced beams. The stage of cracks formation and growth (from 12 to 21 kN) is accompanied not only by a change in the ratio of spectral peaks but also by the appearance of new peaks in the range of higher and lower frequencies (from 2 to 30 kHz). The failure area of the compressed zone of the beam (above 21 kN) is accompanied by a further transformation of the spectrum and a shift toward low frequencies. At the stage preceding the total destruction, a large number of practically equivalent spectral peaks are formed in the spectrum. Similar changes in the spectra of electric signals are observed under conditions of uniaxial compression of concrete [30].

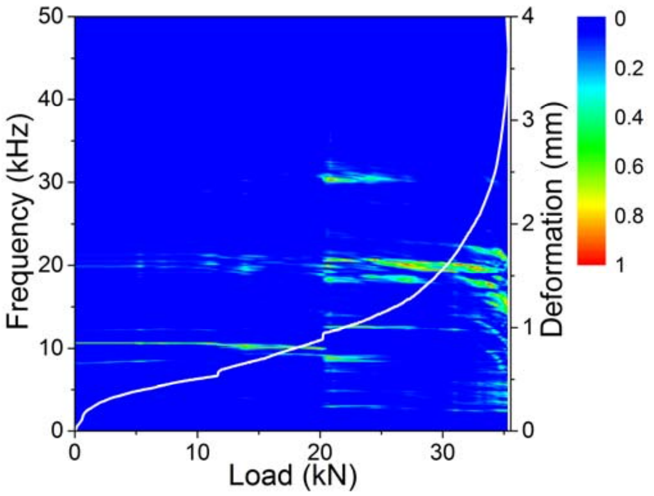

Figure 4. Map of the normalized power spectral density of the electric response during the process of bending a reinforced concrete beam

Next, a quantitative analysis of the transformation pattern of the electric responses amplitude-frequency characteristics under bending test was carried out. To analyse the changes occurring in the spectra of electric responses, two versions of the correlation analysis were used. Comparison of the signals spectra recorded at various loading stages with the signal spectrum registered prior to loading (Figure 5a) and comparison of each analysed spectrum with the signal spectrum recorded at the previous stage of loading (Figure 5b) was made.

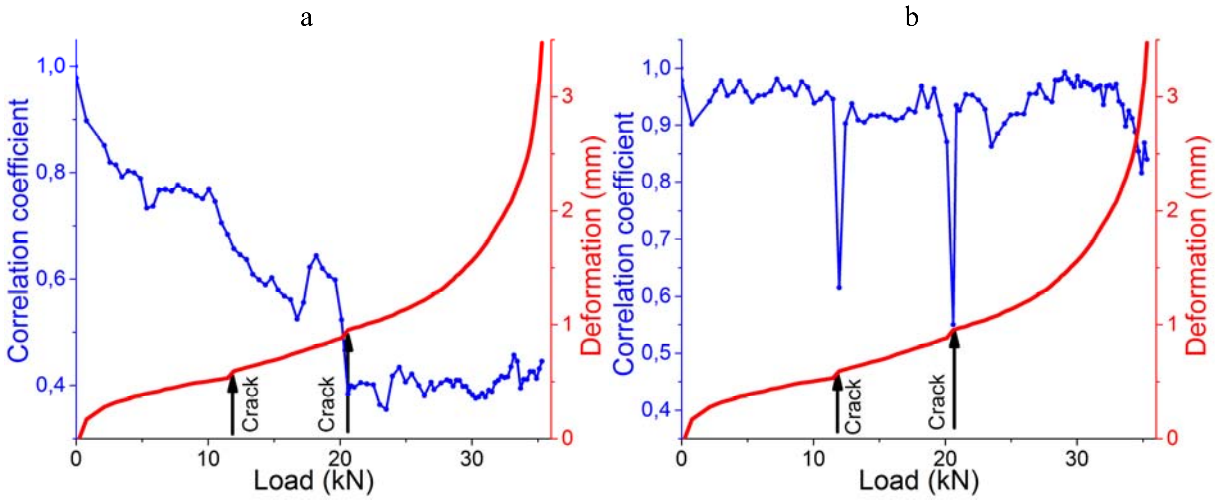

Figure 5. Changing in the correlation coefficient of the signal spectra during the bending process with the spectrum registered prior the loading (a) and with each previous spectrum (b)

The correlation coefficient was determined by the program developed in the LabVIEW programming environment, which allows calculating the current and maximum correlation coefficient of two different spectra and frequency shift at which the maximum correlation coefficient is observed. Our program consequently calculates the correlation coefficients of all signals registered during the beam bending process with the recording of the processing data into a file and the construction of dependencies. As seen from Figure 5b, the appearance of cracks is accompanied by a sharp decrease in the value of the correlation coefficient from 0.95 to 0.6–0.55. The maximum correlation coefficient of the analysed spectrum with the signal spectrum registered before loading (Figure 5a) also decreases at the moments when the cracks appear (at loads of 12 and 20 kN), but not as significantly as in Figure 5b. Thus, the appearance of cracks in the lower stretched part of the beam is more clearly revealed using the correlation coefficient of the analysed spectrum with the signal spectrum registered at the previous stage of loading. Evaluation of the fourth stage of a concrete beam destruction can be more reliably detected by monitoring the changes in the cross-correlation coefficient with the signal spectrum registered from an unloaded (defect-free) beam. When transitioning into the stage of destruction of the beam compressed zone (above 21 kN), the correlation coefficient with the spectrum registered before loading is reduced to 0.35 – 0.4, while a decrease to 0.8 in the correlation coefficient with the previous spectrum is observed only before the total destruction.

Frequency shift change analysis at which the maximum correlation coefficient is observed shows that this characteristic can be used as an additional diagnostic criterion for monitoring of the reinforced concrete destruction (Figure 6).

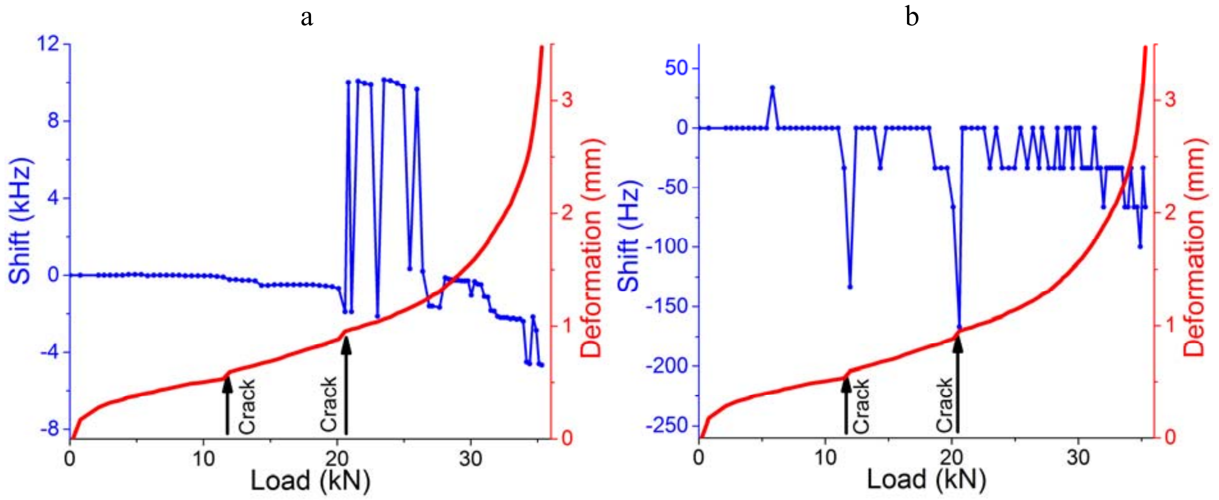

Figure 6. Changing in the frequency shift, at which the maximum correlation coefficient is observed, during bending

As visible from Figure 6, the pattern of change in the frequency shift, at which the maximum correlation coefficient is observed, has the same characteristic features as the correlation coefficient.

4. Conclusions

As part of this work, a comprehensive study of various electric response parameters to an elastic impact has been carried out, and the main regularities of their variation under conditions of a four-point bending have been established. Based on the conducted research, the main diagnostic parameters of the electric response are proposed, according to which it is possible to evaluate the processes of reinforced concrete beams destruction under bending conditions.

It was determined that:

- the appearance of cracks is accompanied by a sharp decrease from 0.95 to 0.6 – 0.55 in the correlation coefficient of the signal spectra registered at different loading stages with the signal spectrum registered at the previous loading stage;
- the correlation coefficient with the spectrum registered prior to loading is reduced to 0.35 – 0.4 when transitioning into the stage of compressed area destruction of the beam;
- catastrophic destruction of the reinforced concrete beam is accompanied by an increase in the energy attenuation coefficient of electric responses by 2 to 2.5 times.

The experimental results showed that the proposed method has the potential for monitoring of concrete damage evolution under bending conditions.

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