Non-linear ultrasonic defectoscopy of concrete structures for nuclear industry

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Abstract. Concrete structures exposed to neutron radiation may exhibit cracking and deterioration, therefore it is needed to find appropriate non-destructive testing methods for assessing their structural integrity. Non-linear wave modulation spectroscopy (NWMS) was developed for non-destructive detection of cracks inside concrete. The goal of this paper is to compare the results of conventional non-destructive and destructive testing methods to the proposed non-linear NWMS method applied to ordinary concrete samples. The concrete damage by neutron radiation was simulated by thermal loading of the samples. Ultrasonic impulse method, resonance method, non-linear wave modulation method, compressive strength and flexural strength testing methods were applied.

Keywords: non-linear ultrasonic spectroscopy, concrete, neutron irradiation.

Introduction

Neutron irradiation of concrete causes damage in the microstructure of the material by the neutron interaction with the material itself and indirectly by the induced thermal heating, which is an issue in the case of biological shields used in nuclear industry (Field, Remec, & Le Pape, 2015). Biological shielding concrete protects the area of reactor vessel and it is hardly accessible for conventional structural diagnostics, while any destructive testing methods are out of consideration. Therefore, non-destructive testing plays vital role in the assessment of the material condition.

Non-linear spectroscopy is based on measuring the elastic-plastic response of the material whose plastic component is caused by microcracks. Part of this response may be caused by inhomogeneity of the material itself or the non-linearity of the test system used, which is to be minimized in the measurement.

Nonlinear wave modulation spectroscopy (NWMS) rests on subsequent transmission of two signals. There are two different approaches of the signals inter-modulation, which can be used on concrete: a) mixing of low-frequency signal (c. 5–20 kHz) and a high-frequency one (c. 70–120 kHz) or mixing of two signals with similar frequencies.

The firstly emitted signal pulses change the width of a crack in dependence of the wave phase. During the compression wave phase the crack closes, meanwhile if the wave is in its tension phase the crack opens. Afterwards, the second signal is transmitted into the material, which is altered by the passage through the crack, more precisely its amplitude changes in dependence of the openness of the crack. If the crack is open at the time (as a result of its interaction with the first signal), the amplitude of the second signal decreases and in case of a closed crack, the amplitude increases. The recorded signal is then analysed using the Fast Fourier transform. For undamaged material there are only two input frequencies found in the obtained spectrum, which were altered only by linear wave dissipation and low atomic nonlinearities. The damage of the material will be demonstrated by the generation of side bands and higher harmonics. This procedure becomes an effective tool of non-destructive testing (Abeele, Desadeleer, De Schutter, & Wevers, 2009; Wang, Lynch, & Sohn, 2014).

This study compares the utility of nonlinear wave modulation spectroscopy with conventional non-destructive testing methods in relation to the results of destructive tests on conventional concrete, which was subjected to heating in order to induce internal damage of the material.

Materials and methods

Materials

Four batches of ordinary concrete with w/c ratio 0.5, silica sand and Portland cement CEM II 32.5 were subsequently mixed to manufacture four series of samples, which were intended to be used as a reference series, resp. series

subjected to heating at temperatures 400 °C, 500 °C and 600 °C. Six cylinders of diameter 100 mm and height 200 mm, eight cubes of edge length 100 mm and nine prisms of dimensions 40×40×160 mm were prepared for each series. The samples were covered with plastic to avoid excess drying for two days, demoulded and then left on air to hydrate for 28 days.

Methods

After the 28-day period, all samples were weighed, measured for their dimensions and tested non-destructively. Afterwards, three series of samples were subjected to heating to 400 °C, 500 °C or 600 °C, reference samples were kept at laboratory conditions at 24 °C. In the case of 400 °C, the temperature was reached in 10 minutes. In both other cases, i.e. series subjected to heating 500 °C and 600 °C, the maximum temperature was reached within 2 hours. The slower increment was chosen due to the crack, which occurred during heating of the series subjected to 400 °C. The dwell time at the final temperature was two hours for all three cases, then the samples were left to naturally cool down. The procedure of dimensions and mass measuring and non-destructive testing was repeated again after the thermal treatment and also destructive tests were used.

Applied non-destructive methods were

- conventional ultrasonic impulse technique, following the Czech standards (ČSN 73 1371: Non-destructive testing of concrete – Method of ultrasonic pulse testing of concrete, 2012);
- resonance method (ČSN EN 73 1372: Non-destructive testing of concrete – Testing of concrete by resonance method on prisms, 2012);
- newly proposed ultrasonic method non-linear wave modulation spectroscopy (NWMS).

Destructive testing included

- determination of compressive strength on cubes, cylinders and prisms (ČSN EN 1015-11: Testing methods for mortar for masonry – Part 11: Determination of compressive and flexural strength of hardened mortars, 2000);
- ČSN EN 12390-3: Testing of hardened concrete – Part 3: Compressive strength, 2002);
- tensile strength on cubes (“ČSN 73 1318: Determination of tensile strength of concrete,” 1986);
- flexural strength on prisms (ČSN EN 1015-11: Testing methods for mortar for masonry – Part 11: Determination of compressive and flexural strength of hardened mortars, 2000).

Non-linear parameter beta can be determined according to formula (1)

$$\beta = \frac{A_{12}}{A_1 \cdot A_2}, \quad (1)$$

here β – non-linear parameter describing the degree of internal defects, e.g. microcracks A_{12} , A_1 and A_2 – amplitudes of peaks in frequency spectra f_{12} , f_1 and f_2 , respectively.

Frequency of the side band (first intermodulation) is calculated as a sum of frequencies f_1 and f_2 ,

$$f_{12} = f_1 + f_2. \quad (2)$$

In particular case, used for this paper, $f_{12} = f_1 + f_2 = 153 + 180 = 333$ kHz.

Results

Bulk density of all series of samples before any conditioning differed in the range of 3% which was within the range of standard deviation (Figure 3, blue line). The evaporation of free water and eventually the removal of bonded water caused the gradual decrease in bulk densities by up to 9% after the heating to 400 °C, 500 °C and 600 °C (Figure 3, orange line). The removal of water and the physical and microstructural changes of concrete components due to heating, such as shrinkage of cement paste or volume expansion of siliceous aggregate caused cracking, being the most pronounced for samples heated to 600 °C (Figures 1 and 2). This was naturally manifested in the tensile splitting strength, flexural and compressive strength of samples.

Figure 1. Photos of selected prism samples after heating to 600 °C (Samples are labelled with the date of preparation and casually selected marks composed by letters and numbers)

Figure 2. Detailed photos of A1 prism's surface from Figure 1 after heating to 600 °C

Figure 3. Bulk density of samples before and after heating

Destructive testing

Figure 4 presents the results of flexural and tensile splitting strength testing measured on prisms of dimensions 40×40×160 mm resp. on cubes 100×100×100 mm. In case of flexural strength, there is a steep decrease in values, reaching only 10% of the initial value after heating to 600 °C. Very similar trend was recorded for values of tensile splitting strength as the drop of values for samples heated to 600°C was by 89%. Also heating to 400 °C resulted in creation of internal defects as the values of flexural and tensile strength were about half the initial values.

Figure 4. Tensile splitting and flexural strength of samples after heating, determined on cubes resp. prisms

Figure 5. Compressive strength of samples after heating, determined on cubes, cylinders and prisms' fragments

Compressive strength was determined on cubes, cylinders and prisms, the values are given in Figure 5. Contrary to the results of tensile splitting and flexural strength, in this case the differences in values determined on samples of various shapes and dimensions were more or less similar. The strength determined on cylinders was always at about 30% lower than on cubes, while values on prisms were lower by 17% for reference state and 400 °C, however for 500 °C the difference was 29% with almost the same value as in case of samples heated to 600 °C, which on the other hand meant 0% difference when compared to values on cubes. Generally, when heated to 600 °C there was a drop in values in the range of 70–75% for all samples when compared to the reference samples.

Non-destructive testing

Figure 6 presents the results of conventional non-destructive testing methods – ultrasonic impulse technique, which gives the modulus of elasticity (E_{bu}) and impact-echo giving modulus of elasticity in longitudinal direction (E_{brL}) and transversal direction (E_{brf}). All values were determined on both prisms 40×40×160 mm and cylinders $d = 100$ mm, $h = 200$ mm, given values are average values with standard deviations. There are insignificant differences in values of modulus of elasticity determined by the different methods. Moreover, the decrease in values more or less relates to a linear dependence in all cases. Also, the decrease in values is profound and so easily detectable, as the drop in values between reference samples and samples heated to 600 °C is by 97%.

Figure 6. Modulus of elasticity measured non-destructively by conventional ultrasound method (E_{bu}) and resonance method in longitudinal direction (E_{brL}) and transversal direction (E_{brf})

Non-linear non-destructive testing

Results obtained by the newly developed method NWMS are presented in Figure 7 in logarithmic scale, again measured on all samples differing in shape and dimensions, i.e. on cubes, prisms and cylinders. Six values were determined for each sample in each group of samples. Average values together with standard deviations were calculated. There is a rise of the parameter beta, which represents non-linearity caused by internal defects, with rising conditioning temperature. The differences in results obtained on different samples' shape and dimensions samples considering the error bars are manifested only in case of reference.

Table 1. Evaluation of non-linear parameter beta for 4 selected prisms

Conditions	Reference	400 °C	500 °C	600 °C
Amplitude A_{12} [V]	0.0000187	0.00004829	0.0000128	0.000001024
Amplitude A_1 [V]	0.0342	0.0301	0.0126	0.000812
Amplitude A_2 [V]	0.0712	0.0214	0.0058	0.00033
Parameter beta [V^{-1}] according to (1)	0.0076	0.0750	0.1752	3.8215

Figure 7. Frequency spectra of prism A1 before a) and after 400 °C heating b)

In Table 1, there are amplitudes A_{12} , A_1 and A_2 , measured in selected prisms – reference, after 400 °C, 500 °C and 600 °C. There are visible differences among the amplitudes which belong to frequency peaks 333 kHz = f_{12} , 153 kHz = f_1 and 180 kHz = f_2 , see Figure 8. Finally, non-linear parameter beta and its calculation is provided in Table 1 according to formula (1).

Values in the Figure 8 belong to all the tested series in average. The ratio to the reference series is 14.4 for 400 °C, 16.8 for 500 °C and 31.0 for 600 °C. This gives a clear picture about the relationship between the damage and the presence of the microcracking, i.e. in case of the first occurrence of microcracks non-linear parameter beta rises rapidly, approximately ten times, after the cracks development and widening there is not so significant increment of beta, which rises “only” by several tens of percents afterwards.

Figure 8. Parameter beta [V^{-1}] as an indicator of non-linearity measured by NWMS displayed in logarithmic scale

Conclusions

The paper aims to present a newly developed non-linear method for non-destructive testing of concrete NWMS and compare its utilization with conventional non-destructive methods used in civil engineering. The methods were applied on ordinary concrete samples of different shapes and dimensions (cubes, cylinders and prisms) subjected to thermal loading at temperatures 400 °C, 500 °C and 600 °C to initiate the uprise of defects inside concrete structure, in comparison to reference samples (without heating). Destructive test were performed to complement the database.

- Flexural and tensile strength decreased by 90% when heated to 600 °C, the shape and dimensions of samples influenced the values for reference samples and samples subjected to 600 °C, while samples heated to 400 °C and 500 °C did not present such high differences in values;
- The drop in compressive strength when heated to 600 °C was by 70–75%, while the difference between values determined on different groups of samples were approximately the same for all heating states;
- Values of modulus of elasticity obtained by conventional ultrasound and resonance methods decreased by 97% when heated to 600 °C and showed a linear dependence of its values on the conditioning temperature;
- Non-linear parameter beta obtained by NWMS did not show any clear dependence on temperature as the rest of the methods, but proved itself to be very sensitive to the presence of any defects in the internal structure of concrete, as the rise of values for samples heated to 400 °C when compared to reference samples was by one order of magnitude.

Acknowledgements

This work has been supported by the Ministry of Education, Youth and Sport in the Czech Republic – LQ1603 Research for SUSEN and internal project: Monitoring of concrete cracks via neutron noise analysis.

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