EXPERIMENTAL INVESTIGATIONS OF ACOUSTIC EMISSION FROM THE VIEWPOINT OF ITS USE TO DETECTING THE REINFORCED CONCRETE ARMATURE CORROSION

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Abstract
Application potential of the acoustic emission method to evaluating the changes in the internal structure of reinforced concrete specimens which are due to the steel armature corrosion has been studied in this paper. Corrosion of built-in steel reinforcement elements ranks among the most serious mechanisms of impairing the reinforced concrete structure stability. The armature corrosion may be due to various reasons, such as improper procedures having been applied during the construction process, structure utilization and/or ageing. Visual inspection of structures provides general information on the structure condition as viewed from the outside; however, it cannot provide any information on the building structure internal structure and integrity. Therefore, non-destructive methods of determining the integrity of these structures or their parts are being looked for. They are expected to help implementing appropriate maintenance, servicing, repair or reconstruction measures to be applied to building structures. One of the methods, whose application appears promising from this viewpoint, is the acoustic emission method. The method was applied to reinforced concrete specimens containing non-corroded armatures as well as to those subjected to accelerated corrosion. Reinforced concrete specimens were subjected to cyclic loading in a pressing machine. Specimen response to flexural tensile load was studied. Cumulative counts of acoustic emission overshoots versus specimen mechanical stress plots were evaluated. Manifestation of the Felicity effect in the case of cyclic loading was also studied. Our results have proved the existence of a correlation between the changes of selected acoustic emission parameters and the consequences of progressing corrosion in degraded specimens.

Key words: Reinforced concrete, armature corrosion, accelerated corrosion cyclic loading, acoustic emission

1. Introduction

Stability of building structures is one of very important issues in the field of non-destructive defectoscopy. Taking into account the fact that most of concrete and reinforced concrete structures were built in the first half of last century, it is evident that a search for new and simple defectoscopic methods, allowing the researchers to determine the integrity of these building structures or their parts, is of primary importance. Bridge structures make an important element of the traffic infrastructure. Most of these bridges are made of reinforced concrete, usually pre-stressed one. Their safety, regular maintenance and satisfactory technical condition are essential for keeping the traffic continuity and smoothness. Corrosion of the steel armature ranks among the most severe stability threatening factors. The reasons
for the corrosion to occur are various: failures occurring during the bridge construction, consequences of traffic load or, simple ageing of the structures.

Visual inspection of a bridge provides general information on the bridge condition. However, it cannot provide any information on the internal structure and integrity of the reinforced concrete or pre-loaded elements of the bridge in question. This is why non-destructive diagnostic methods are acquiring growing importance, helping the researchers to evaluate properly the condition of a bridge and decide upon the most convenient methods for maintenance, repair or refurbishment of the bridge in question or its parts and schedule them accordingly. One of the methods, which is recognized worldwide as the most promising for the mentioned purposes, is the acoustic emission (AE) method. By contrast to most other NDT methods, AE is a comprehensible method, allowing both one-shot examination and long-term monitoring of the condition of the structure under consideration or its selected parts.

2. Steel armature corrosion

In addition to mechanical stress, structure materials are exposed to a more or less aggressive environment, whose effect results in corrosion. Under the term corrosion, a spontaneous process of physical or chemical deterioration of materials under the action of a liquid or gaseous environment, is understood.

In general, it can be stated that the steel armature corrosion origin and progress depend on the concrete impermeability, cover layer thickness and quality, cement grade, hardening conditions, admixtures used and crack generation rate and size. Whereas the strength of concrete usually increases in time, the protective function of concrete with respect to the steel reinforcement elements diminishes gradually. Once chloride ions reach the armature, the armature passivation layer will be damaged. The time during which the ions are able to do so depends on the penetration mechanism, external chlorine ion concentration and concrete permeability.

The steel armature corrosion gives rise to cracks and subsequent peeling of cover layers, which in turn leads to the loss in strength of reinforced concrete structures. Determination of the steel armature corrosion degree is an inevitable criterion for the decisions to be taken concerning the maintenance or redevelopment procedure for reinforced concrete elements.

3. The acoustic emission method

The acoustic emission method is one of non-destructive methods, which is applicable throughout a wide range of materials. Under the acoustic emission phenomenon, we understand a process of generation and propagation of stress waves of phonons, which have been released in a local dynamic rebuilding of the material internal structure. Applied stress or aggressive environment may give rise to internal changes in the structure, such as crack growth, local plastic deformations, corrosion or phase transitions. These changes are, in general, accompanied by emission of elastic waves, which are carrying information on the material internal behaviour. These waves can be detected by an acoustic emission pick-up element, or sensor, which detects a combination of longitudinal, transverse and surface waves coming from several directions to transform them into an electric signal. The signals are further processed in appropriate instruments designed to detect, characterize and locate the acoustic emission sources.

By means of the acoustic emission method, structure impairment and deterioration caused by various mechanisms can be detected.
Based on the frequency of the mechanical waves emitted, two types of sources can be distinguished:

The low-frequency (impulse) acoustic emission type, which is due to processes running in the material surface. As a rule, these processes consist in generation of micro- and macro-cracks occurring in the course of test specimen loading. These sources are external in nature. They are triggered by interactions with rigid bodies, liquids or gases and mechanical or electrical waves.

The high-frequency acoustic emission type is given rise by mechanisms running inside the material. The sources of these signals consist in changes on the micro-level.

The cause of the emission source emergence can be determined from the behaviour of this source in the course of increasing and decreasing the load and, furthermore, from the nature of the emission events stemming from this source. Among the main features of a crack-induced emission source, there are the following: Kaiser effect (Fig. 1), emission active nature and high emission intensity.

The Kaiser effect is a phenomenon, in which the emission source is only active if the stress exceeds the limit, which has already been formerly attained. Such a source is emitting neither during the load decrease phase nor during a repeated load increase up to the formerly attained value [1].

Another phenomenon of importance is the Felicity effect, which is defined as the occurrence of notable acoustic emission at a lower load than the previous maximum level. This phenomenon has been observed, above all, in composite materials. The operation of Kaiser effect proved to be incomplete in the case of concrete. The structure, for example, a reinforced concrete beam, can „heal“ and the load-induced acoustic emission can appear sooner than in the previous loading experiment. Nevertheless, this effect can be taken advantage of as follows: if the Kaiser effect ceases to operate, it means that „tensile“cracks are gaping open and „shear“cracks are arising. To express the relevance of this effect, the so-called Felicity ratio, indicating the ratio of the load level causing the repeated occurrence of pronounced acoustic emission and that corresponding to the previous maximum load, is introduced. The lower this ratio, the poorer is the condition of the structure. This method of evaluating the structure is being applied to laboratory tests, where cyclic loading and relieving of structures can be carried out. As far as bulkier structure diagnosing "in situ" is concerned, this method is difficult to apply.

![Fig. 1  Kaiser effect, Felicity effect and Felicity ratio](image-url)
The application of the acoustic emission methods to the investigation of structural integrity of elements or structures is based on the finding that the acoustic emission accompanies not only fracture processes but also any material gradual degradation processes. The AE method has a definite advantage over other methods, i.e., the selectivity – it is able to detect only such defects which are unstable during the structure loading (not in absolute magnitude, but only as magnitude changes).

4. Experiment

The subject of our experiments consisted in concrete and reinforced concrete specimens of dimensions 100 x 100 x 400 mm. The ensemble of reinforced concrete specimens consisted of 8 specimens containing a steel bar of a diameter 10 mm (of which 4 specimens were subjected to accelerated corrosion), eight specimens with a 8 mm diameter steel bar (of which 4 specimens were subjected to accelerated corrosion) and a single specimen containing no armature. The accelerated corrosion consisted in cyclic soaking of the specimens in a bath containing a 3% water solution of sodium chloride and subsequent drying.

The specimens were subjected to cyclic loading in a pressing machine. The loading consisted in three cycles, with maximum stress forces of 3 kN, 6 kN and 10 kN. The specimen stress versus time plot is shown in Fig. 2. Acoustic emission impulse counts were picked up during the stress tests. Selected acoustic emission impulses were recorded and saved to be subjected to frequency analysis.

Cumulative frequency of AE events versus attained specimen stress plots have been evaluated (see the diagrams in Figs 3 through 7). Figure 3 represents the AE cumulative activity for loading of a specimen containing no armature. It is evident from the diagram that irreversible changes have taken place in the specimen even during the first stress cycle, as the Kaiser effect did not apply and the Felicity effect was operating starting from the second stress cycle.

Fig. 2 Specimen stress versus time plot

4.1 Measurement results

Cumulative frequency of AE events versus attained specimen stress plots have been evaluated (see the diagrams in Figs 3 through 7). Figure 3 represents the AE cumulative activity for loading of a specimen containing no armature. It is evident from the diagram that irreversible changes have taken place in the specimen even during the first stress cycle, as the Kaiser effect did not apply and the Felicity effect was operating starting from the second stress cycle. Fig. 4 shows the measurement results for a diameter 8 mm armature specimen, which has not been subjected to forced corrosion. Kaiser effect is apparent to occur between the different cycles in the diagram of this Figure. The growth in the AE event frequency is slow, following a straight line up to the specimen tension of about 4.5 MPa. Starting from 5 MPa, an abrupt
growth of registered AE event counts is observed. The 8 mm diameter armature specimen (corroded) shows the Felicity effect between the second and third stress cycle (Fig. 5). This brings us to a conclusion that the bond between the armature and the concrete has been impaired during the second cycle. Starting from a tension of 3 MPa, an exponential growth in the AE event counts is apparent in the diagram.

Fig. 3 Cumulative AE – specimen with no armature

Fig. 4 Cumulative AE activity – non-corroded specimen with 8 mm diameter armature

Fig. 5 Cumulative AE activity – corroded specimen with 8 mm diameter armature
Analogously, Figures 6 and 7 show the cumulative loading-induced AE activity of 10 mm diameter armature specimens. The shape of the curves in both Figures is almost the same. Kaiser effect operated between the different cycles, from which it is evident that the bond between the armature and the concrete has not been impaired by corrosion.

![Cumulative AE activity – non-corroded specimen with 10 mm diameter armature](image1)

**Fig. 6** Cumulative AE activity – non-corroded specimen with 10 mm diameter armature

![Cumulative AE activity – corroded specimen with 8 mm diameter armature](image2)

**Fig. 7** Cumulative AE activity – corroded specimen with 8 mm diameter armature

When analyzing the AE signal records, we focused, first of all, on the occurrence of frequency components from 100 kHz to 300 kHz, which are related to the corrosion of the steel armature in concrete [2-4]. Fig. 8 compares the frequency spectrum of a plain concrete specimen with that of reinforced concrete specimens subjected to accelerated corrosion. Curve 1 corresponds to a plain concrete specimen. Here, the maximum amplitudes occur in the neighbourhood of a frequency of 60 kHz, corresponding to the concrete impairment. In the case of curve 2, corresponding to a 10 mm diameter armature reinforced concrete specimen, the amplitudes are reaching higher absolute values throughout the frequency band and, simultaneously, the predominant components are shifted towards lower frequencies. The 150 kHz component is emphasized, too, indicating the generation of microcracks and segregation of the armature from the concrete [2-4]. Curve 3 corresponds to a 8 mm diameter...
armature reinforced concrete specimen. In this frequency spectrum, a growth of amplitudes in the frequency band of 60 kHz upwards occurs. Furthermore, amplitudes of 225 to 250 kHz frequency components, corresponding to signals arising in consequence of structure impairment of the corrosion layer [2-4] are emphasized, too.

Fig. 8 Frequency spectra of a plain-concrete specimen (1) and corroded reinforced concrete specimens (2, 3)

5. Conclusion

Based on the above mentioned results, it can be stated that the first parameter under investigation – the acoustic emission impulse cumulative frequency – showed the Felicity effect during the stress tests, thus providing information on the generation of irreversible structure defects. In the case of plain concrete specimen (Fig.3), the Felicity effect was registered between all stress cycles. For reinforced specimens, the impulse cumulative frequency curves provide information on the acoustic emission impulse counts for various specimen stress magnitudes. In the corroded specimen case (Fig. 5), showing also the Felicity effect between the first and second cycle, the source of these signals consisted obviously in microcracks arising in the binder in the armature neighbourhood, in consequence of the incipient armature corrosion. It is thus confirmed [5,6] that the occurrence of the Felicity effect during the cyclic stress tests gives evidence of irreversible structure defects taking place in the material. These defects may be due to both lower specimen strength (plain concrete) and deterioration of the armature-to-concrete bonds in consequence of the armature corrosion.

Also the second parameter – the cyclic-loading-induced response frequency spectrum - proves to correlate with the structure quality in the specimens under investigation. Armature corrosion-induced structure defects take effect in changes of the frequency spectra.

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References


