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Identification of the reinforcement bars in concrete samples using eddy currents thermography

Abstract

It is known that sub-surface discontinuities of matter, internal voids, inclusions of other materials or delaminations of the structure can be revealed on the surface temperature distribution. An important element of IR thermography investigations is the application of an appropriate heat source to heat the examined object. This article discusses the use of eddy currents for identification of reinforcing bars in concrete samples. The experiments have the laboratory character and are used primarily for qualitative assessment of the influence of bar diameter and concrete cover thickness on the identification of reinforcement in concrete elements. In order to induce a transient heat flow in tested samples, the eddy currents (EC) generator from IFF GmbH was used. After the pulse was completed, the surface temperature distribution was recorded using FLIR T620 infrared camera. The following experimental studies validate the practical application of active IR with EC to locate and assess the technical condition of reinforcing bars in reinforced concrete structures in buildings and civil engineering structures.

Keywords: active IR thermography, eddy currents, reinforcement bars.

1. Introduction

The problem of identifying damage in reinforcement bars of reinforced concrete engineering structures (viaducts, bridges, supporting walls, etc.), due to their function and importance for transport, is a current and extremely important engineering challenge. There are several methods of identifying the characteristics of reinforcement (diameter, depth of the placement, degree of corrosion or cracks), but one of the most interesting is infrared thermography combined with eddy currents. The theoretical and physical basics of infrared thermography with a description of its practical applications can be found in Polish monographs [1, 2, 3]. A problem of detection and description of reinforcement features of massive reinforced concrete beams is presented in [4]. The description of lock-in thermography technique for the detection of cracks in electroconductive materials using eddy current generators as heat stimulation sources can be found in [5]. In the paper [6] numerical simulations and experimental verifications of pulsed EC thermography for identification of features of an angular slot inside an aluminum sample has been conducted. The article [7] published the results of numerical simulations, which are the first step of research preceding the possible use of ECT for the detection of micro-cracks, delaminations, corrosion etc. damages in metal hulls of marine ships. Szymanik et al. [8] propose a new concept of concrete structures analysis using microwave heating as a preliminary technique to reinforcement bars detection and the multi-frequency eddy current method as a complementary diagnostic tool. Interesting and successful investigations on the influence of corrosion of steel bars, the technique of its detection and determination the corrosion level in concrete samples using numerical simulations and laboratory tests are presented in [9]. The concept of crack detection called line-scanning method is described in [10]. He et al. used the idea to move the coil at a certain speed along arbitrarily defined lines over the surface of the object, like a typical scan.

This article is a continuation and extension of the previously presented research of Authors [11] concerning damage detecting in a reinforced concrete slab (also numerically simulated) and in a real concrete bridge. In this article we aim to examine the possibilities and limitations in detecting some features of steel bars in concrete samples using active IR thermography associated with eddy current excitation.

2. Problem formulation

The basic phenomenon used in the eddy current method is electromagnetic induction, as defined by Faraday's law. The alternating current flowing through the coil produces an alternating magnetic field in it, which induces an electromotive force in the material under investigation. This force generates eddy currents, which flowing through the body causes the release of heat in it (according to the law of Joule-Lenz). The heat generated in this way is observed and recorded in time by means of an IR camera on the surface of the examined body. Any disturbances in the structure of the tested material influence the intensity of eddy currents and the surface temperature distribution.

The use of eddy currents in combination with infrared thermography is a diagnostic technique used for many years. However, the use of this method for the diagnosis of reinforced concrete structures is a novelty. It can be used either at the production stage or during the exploitation period for detection:

- surface and internal material defects of the rolled products,
- internal material defects of iron castings,
- defects of welded joints,
- external corrosion of reinforcing bars and intercrystalline corrosion,
- defects in electrically conductive composite materials.

The advantages of IRT and EC are as follows:

- lack of reflections of radiation and other artifacts, which are related to reflectivity of the surface, its roughness or other factors - which is an essential part of thermography with excitation by means of e.g. halogen lamps,
- easiness and speed of stimulation,
- detection of very small surface and subsurface defects,
- possibility of automation and processing of the obtained results.

The aim of this research is to determine whether EC thermography can be an effective and practical tool for technical condition diagnosis, defect detection and the recognition of the placement of reinforcement bar nets under the surface of concrete structures. This is a multidimensional and complex task, Therefore the research has been divided into two parts. The first part of the research consisted in the analysis of the influence of the parameters of the eddy current generator, the distance of the coil position in relation to the surface of the rod and the orientation of the rods on the character of the induced heat flow. The second part of the research was carried out on concrete samples in which single rods of different diameters were concreted. These studies focused on the analysis of the distribution of heat recorded on the concrete surface depending on the location of the coil and the thickness of the bar cover layer.

3. Laboratory tests

The research was used to verify the potential of the proposed method in terms of the qualitative aspects and to test various parameters of thermal excitation. For the first step of the research, 7 ribbed bars of the B500SP steel type, commonly used in reinforced concrete structures, with a length of approximately 20 cm and the following diameters, were used: 6, 8, 10, 12, 14, 16 and 20 mm (Figure 1a). The second part of the research was carried out on 8 small concrete blocks with dimensions of 16×20×5 cm. In seven of them single bars of the above mentioned diameters were concreted, and one sample, as a reference, was made without reinforcement.

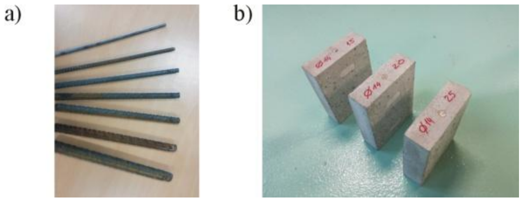

Fig. 1. Examples of samples used for the tests: a) reinforcing bars of diameter: 6, 8, 10, 12, 14, 16, 20 mm, b) concrete elements with dimensions 16×20×5 cm

The bars were placed in concrete blocks in such a way that the thickness of the concrete layer, relative to the observed surface was 1.0 cm. In the three another concrete blocks, the 14 mm diameter bars were located in the samples so that the thickness of the cover layer was achieved: 15, 20 and 25 mm. (Fig 1b).

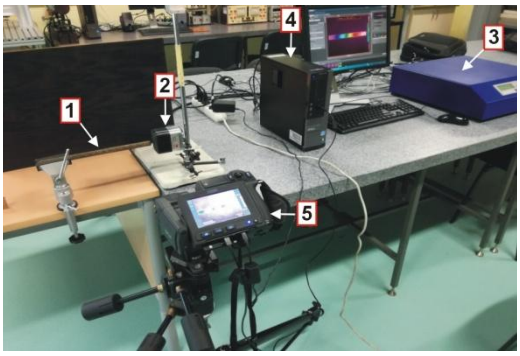

Fig. 2. View of elements of the measuring system during EC thermography tests: 1 – steel bar, 2 - IFF 0616 coil, 3 – IFF EC generator type EW030F, 4 - computer, 5 – T620 IR Camera

The experiments have been fulfilled by means of a FLIR T620 IR camera (NETD up to 50 mK, FPA 640×480, (7,8÷14) μm. The eddy current excitation was performed with the aid of IFF GmbH equipment. The eddy current excitation was performed with the aid of IFF GmbH equipment. The frequency of the generated signal can be changed from 10 to 30 kHz. The pulse width and power modulation in relation to the period of the generated signal is determined by the Pulse Width Modulation (PWM) option in the range from 0 to 750‰. A setting of e.g. 100‰ means that the current flows for 1/20 of the period (i.e. short) and the heating is weak. The maximum operating time of the eddy current generator is 100 seconds. Fig. 1 presents the set-up used for conductive tests with eddy current thermography.

3.1. Recognition tests

Taking into account the placement of bars in typical reinforced concrete structures, the problem of selecting the proper localization as well the way in which the coil affects the examined object arises. To recognize this issue, the impact of a number of factors related to the configuration of the coil-steel bar was analyzed:

a) the position of the bars in relation to the coil was variable,
b) the distance between the surface of the bars and the coil was variable,
c) the parameters of the eddy current generator were variable.

3.1.1. Heating of the bars from the front face

At this stage, the tests were used to assess the possibility of heating the steel bar when the coil is close to its end. The heat wave propagation caused by alternating eddy currents, by the conductivity, results in heat propagation along the bar. After the EC generator has finished its operation, the steel bar cools down - rapidly at the coil location, much slower in sections located far from the end of the bar. The process of thermal stimulation and the cooling phase was observed and recorded with the IR camera for about (5…6) minutes. In Fig. 3, the measurement stand is presented as well as a scheme describing the basic elements and parameters of the test.

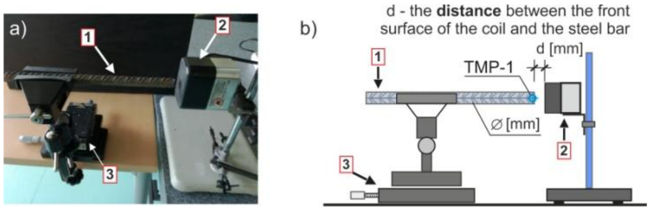

Fig. 3. Thermographic investigation by means of EC: a) a photo of the measuring stand: 1 - steel bar, 2 - coil, 3 - goniometric table, b) scheme of the stand with the location of the temperature measurement point TMP-1

The value of the maximum temperature obtained in steel bars during the tests depends on the diameter of the bar, the distance between the front surface of the coil and the surface of the steel bar (described by the symbol *d*) and on the signal parameters: the frequency *f*, the PWM parameter value and time. Regardless of other parameters, the larger the diameter of the stimulated bar, the greater the heat generated by the coil. This depends on the size of the cross-sectional area on which the coil affects. Let us note that the coil was always symmetrically positioned with respect to the longitudinal axis of the bar. Several tests have shown that shifting the coil up or down ((3…5) mm) from the axis of the bar does not significantly affects the distribution and power of the heat generated. The influence of changes in the parameters of the pulse itself was not investigated on the assumption that the full power of the generator and its maximum operating time should be used. Therefore, the maximum values of PWM parameters 750‰ and pulse duration of 100 seconds, resulting from the factory settings of the EC generator, were assumed.

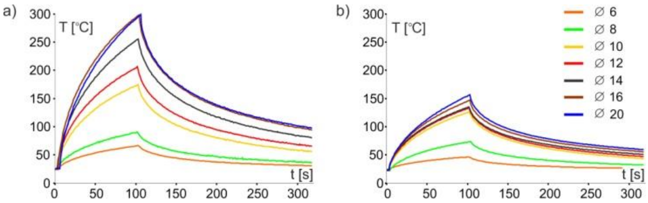

Fig. 4. Temperature profiles for TMP-1 point for the respective steel bars for: a) *f*=12 kHz, b) *f*=30 kHz

The influence of the frequency of the generated signal on heat stimulation was investigated. In order to reduce the number of tests, two test sequences were performed at *f*=12 and *f*=30 kHz. It appeared that at the frequency *f*=12 kHz after 100 seconds in a 20-mm diameter bar a temperature value of 298.7°C was obtained at the TMP-1 point, whereas at the frequency *f*=30 kHz, 156.3°C. The graphs in Fig. 4 show the temperature distribution in time at the TMP-1 measuring point when the distance between the coil and the bar was 2.0 mm for both frequencies. There is a clear dependence of the generated power on the frequency and diameter of the bar. From the researches described in the literature, it is known that the frequency change of excitation is used to identify sub-surface defects (then higher frequencies are recommended) or to identify deeper defects (then lower frequencies are used). Experimental results show that for higher signal frequencies a lower temperature was generated in the tested bars. This is most likely due to the skin effect, as a result of which eddy currents flow through the smaller "cross-sections" the higher the frequency is.

The graphs in Figure 5 show the temperature profiles at TMP-1 point for all steel members depending on the distance value at a pulse frequency of 12 kHz. The higher the distance value, the weaker the eddy current field generated by the coil in the steel bars.

The tests were carried out in a laboratory where the air temperature was T_{air}=22.5°C with relative humidity R_h=45.6%. The IR camera was set so that the distance between the lens and the tested bar was 40 cm. Based on the literature, the value of the emissivity coefficient of the bar surface equal to ε=0.8 was assumed.

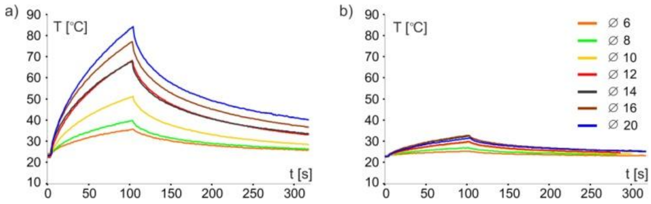

Fig. 5. Temperature profiles for TMP-1 point at a pulse frequency of 12 kHz for distance equal: a) d=10 mm, b) d=20 mm

3.1.2. Impact of the distance between the coil and the bar

Due to the fact that the reinforcing bars are under the surface of concrete, the effectiveness of their excitation with the EC coil and the possibility of their identification by thermographic method is primarily determined by the value of the distance parameter (d). In order to analyze this problem, a number of tests were conducted on a 14 mm diameter bar at variable coil distances. The distance parameter d was varied between 1 to 25 mm in 1.0 mm intervals. The distance from the coil face to the bar surface was determined precisely using gauge blocks. Each subsequent registration required waiting about (15…50) minutes until the steel bar cooled down completely. The experiments were performed for the following parameters: f=12 kHz, t=100 seconds, T_{air}=22.8°C, R_h=44.8%, the distance between the camera and the object was 30 cm. Fig. 6 shows the obtained relationship between the temperature recorded at the end of the bar and the distance of the EC coil to the bar.

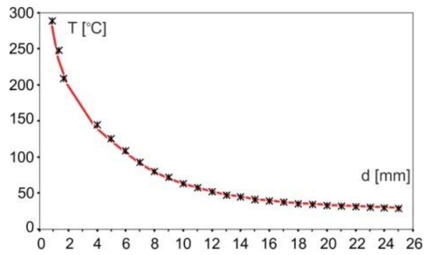

Fig. 6. The influence of the distance between the end of the bar and the coil on the maximum temperature values obtained at the end of the 14 mm diameter bar

3.1.3. Influence of the bar position

If the actual reinforced concrete structures were to be tested, the position of the steel members in relation to the coil would usually be perpendicular. Thus in the next experiments, the bar was attached vertically in a tripod, means perpendicularly to the axis of the coil. The particular bars were located in relation to the EC inductor with a constant distance of 10 mm. The distance between the IR camera and the object was 0.6 m, the temperature in the laboratory room was T_{air}=23.2°C, and the humidity R_h=42.3%. Fig. 7 shows a measurement stand and an example thermogram for a 12 mm diameter bar at a time t=60 s with a description of the measurement point TMP-1. Interesting features of temperature decay were observed in TMP-1 point for 6 mm diameter bar (Fig. 7c). The temperature values are now higher for ∅6, 8, 10 and 12 mm bars than in the previous tests (see Fig. 4). In this case, the EC excitation caused higher temperatures in thinner rods, e.g. in a ∅6 mm bar the temperature value reached T=413.0°C.

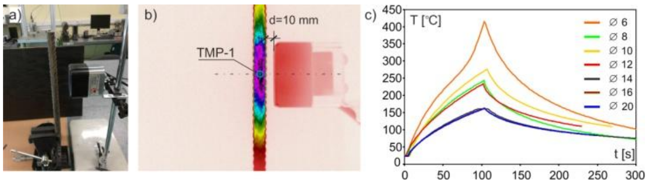

Fig. 7. Thermographic investigation by means of EC: a) a photo of the measuring stand, b) thermogram at time t=60 s of ∅12 bar, c) the temperature profiles for TMP-1 point for all bars

In order to compare the nature of the heat distribution, an additional test was carried out for a 14 mm diameter bar by increasing the dilatation value to 25 mm. The excitation effect and results at TMP-1 point and TML-1 line are shown in Figure 8.

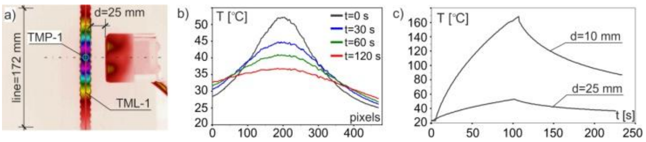

Fig. 8. Thermographic test results for 14 mm diameter bar: a) thermogram at time t=0 s after excitation, b) the temperature profiles for TML-1 line at different moments in time, c) the temperature profiles for TMP-1 point depending on d

3.2. Investigation of concrete samples

The second stage of the study was to verify the results obtained from the testing of single steel bars. Seven small concrete specimens with single bars were prepared for testing (see Chapter 3). The research consisted in thermal stimulation of the concrete bars with a coil producing an alternating electromagnetic field, whose setting was adjusted in two different ways. Once the coil was located on top of the sample, directly above the end of the rod (Fig. 9a), the second time the coil was placed in front of a concrete block to heat the steel bar through a 1.0 cm thick concrete layer (Fig. 12a).

We hope to use the following preliminary research to identify defects in both reinforcement and concrete in the future. At this stage, the experiments have helped us to better identify the nature of thermal stimulation in reinforced concrete elements using the EC technique.

The tests were carried out in a laboratory where the air temperature was T_{air}=22.8°C with relative humidity R_h=45.2%. The IR camera was set at a distance of 63 cm from the tested concrete element. The value of the emissivity coefficient of the concrete surface was assumed to equal to ε=0.95.

3.2.1. EC thermography of the concrete samples from the top

The test results show a strict dependence of certain groups of steel bars (e.g. with diameters of 6 and 8 mm or 10 and 12 mm, etc.) on the temperature distribution of the surface of the concrete sample over time. Analyses of experiments also reveal a certain thermal inertia resulting from the presence of 10 mm thick concrete lagging. This inertia depends on the diameter of the steel rod and is much smaller for larger diameters than for smaller. For a ∅6 mm bar, it is about 20 s (according to the temperature profile analysis at TMP-1 point) and about 35 s (based on thermogram analysis).

The chosen distance between the coil and the top surface of the concrete element d = 10 mm proved to be safe. In none of the tests did the temperature in the concrete sample exceeds the value of 37°C. In general, the larger the diameter of the rod, the more intense and longer the heat propagation process in the concrete sample is, as shown in Fig. 9b.

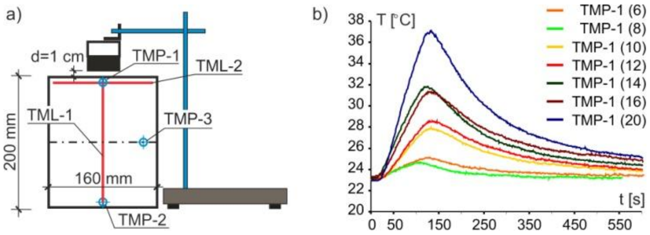

Fig. 9. Thermographic investigation by means of EC: a) illustration of the test stand scheme, b) time temperature profiles for the point TMP-1 for particular concrete elements (the value in brackets is the diameter of the steel bar)

The graphs in Figure 10 show the temperature profiles along the TML-1 and TML-2 lines for the time moment t=145 s (i.e. just after the coil is switched off) for all seven concrete samples.

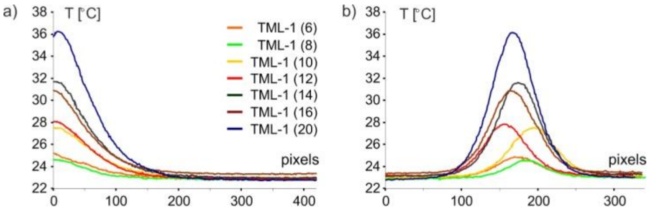

Fig. 10. Temperature profiles at time=145 s for different concrete elements for: a) the line TML-1, b) the line TML-2

Figure 11 shows representative thermograms for different bar diameters and time moments, showing the nature of heat propagation in concrete. For 6 and 8 mm diameter bars, the thermal "response" to the EC excitation is small and limited to a very small area of the sample surface.

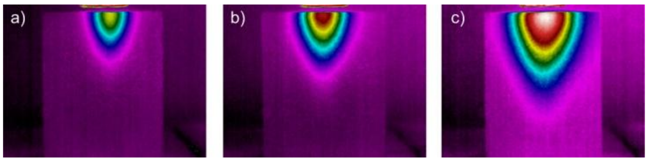

Fig. 11. Thermograms for different concrete samples at different time after thermal stimulation: a) sample with 10 mm bar at the time of t = 60 s, b) sample with 14 mm bar at the time of t = 120 s, c) sample with 20 mm bar at the time of t = 240 s

3.2.2. EC thermography of the concrete samples from the front

In this part of the EC thermography research, the coil was positioned axially and centrally in relation to the concrete specimen in a distance of about 2 mm from its front surface. In this situation (Fig. 12a), the generation of heat in the bar by the coil is limited by the concrete cover with a thickness of 10 mm. These tests are slightly reminiscent of the experiments described in Chapter 3.1.3. Due to the fact that the coil obscured the observed surface of the sample during the 100 second heating period, the experiment was divided into two phases (Fig. 12c). The first phase related to thermal stimulation was not analyzed. After the EC generator shutdown, the coil was immediately removed and the second phase took place, i.e. the recording and analysis of the process of concrete surface cooling with the use of IR camera.

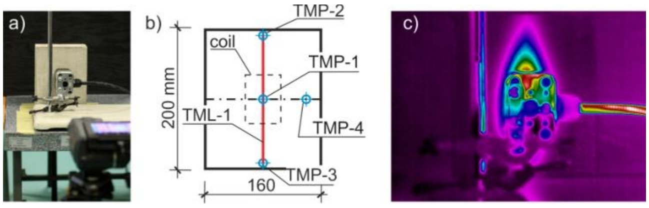

Fig. 12. Thermographic investigation by means of EC: a) a photo of the measuring stand, b) scheme of the sample with the location of the measurement points, c) thermogram at the time t=100 s

The diagram of measurement points layout is shown in Fig. 12b. The temperature profiles along the TML-1 line for the time t=30 s after the stimulation is completed and the temperature profiles at TMP-1 point for all concrete elements are presented in Figure 13. What is interesting, the generated eddy currents in bars with smaller diameters (e.g. 8 and 10 mm) cause stronger heating of concrete elements. However, there is no clear relationship between the intensity of the heat generated and the diameter of the steel bar. Let's just remember that during the preparation of samples, despite due diligence, the obtained thicknesses of the concrete covers may be different for each individual element. We estimate that the cover thickness deviation may be approximately (1…2) mm, which may affect the test results.

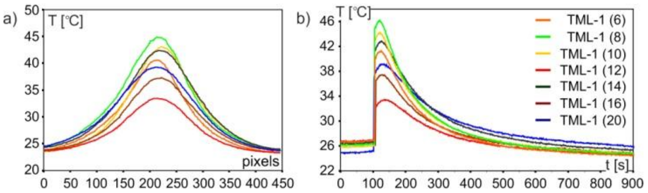

Fig. 13. Temperature profiles for different concrete elements for: a) TML-1 line at the time of t=30 s after thermal stimulation, b) the point TMP-1

The received results show that especially this type of stimulation gives the possibility to generate heat distribution on large areas of the tested elements (see Fig. 14). This is an indication of the high potential of this technique for thermal stimulation of real reinforced concrete elements.

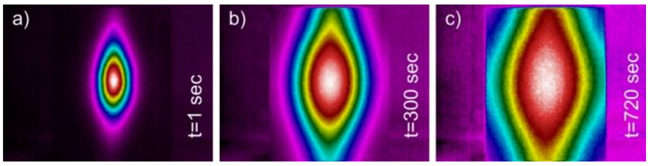

Fig. 14. Thermograms for a concrete sample with a ∅20 mm bar at different time moments after thermal stimulation: a) at the time of t = 1 s, b) at the time of t = 300 s, c) at the time of t = 720 s

3.2.3. Influence of the cover thickness

The influence of the thickness of a concrete cover layer on the possibility of thermal stimulation of a steel rod does not cause radical limitations in the use of the diagnostic technique proposed in this article. In the context of the standard thickness of concrete cover of reinforcement bars (c_{nom}=(25…40) mm), this is a very positive discovery. Three concrete elements were made, each with a steel bar with a diameter of 14 mm (Fig. 1b). The bar was placed in such a way that the thickness of the concrete cover was 15, 20 and 25 mm, respectively (in relation to the stimulation/measuring surface). The steel bar was stimulated by a coil placed over the upper surface of the concrete element as in Chapter 3.2.1, but the distance between the coil and the bar was reduced to about (2…3) mm in order to induce a stronger excitation. Similar temperature distributions were obtained as in tests 3.2.1, whose character changed with the change of the thickness of the concrete cover (compare Figures 9b and 15b). An example of a thermogram for a concrete element with a steel bar cover layer c=15 mm is shown in Figure 15a.

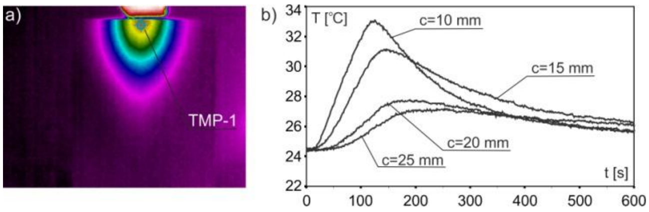

Fig. 15. Influence of concrete cover thickness on heat distribution by EC stimulation of the sample at the top: a) thermogram at the time t=30 s after excitation for a concrete sample when c=15 mm, b) temperature profiles at TMP-1 point

Additional experiments have been carried out when the steel bar is stimulated by the coil, through the variable thickness of the cover, from the front of the concrete slab (as in Section 3.2.2). Thermal stimulation with EC is still possible, but with a concrete cover thickness of 2.0/2.5 cm, the temperature gradients and the heat distribution area in relation to the concrete sample are much smaller. Some examples of the results are shown in Figure 16b.

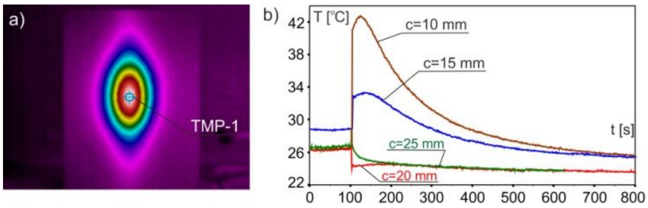

Fig. 16. Influence of concrete cover thickness on heat distribution by EC stimulation of the sample at the front: a) thermogram at the time t=30 s after excitation for a concrete sample when c=15 mm, b) temperature profiles at TMP-1 point

4. Conclusions

The results of the current research show that the eddy current thermography is an interesting and perspective NDT tool for the identification of reinforcement bars. The main conclusions of the study are as follows:

- the process of indirect concrete heating is slow and lengthy, depending on the diameter of the steel bar and the thickness of the concrete cover layer,
- the application of EC allows obtaining a distinct temperature distribution on the surfaces of concrete samples, which makes it possible to use this type of thermal stimulation for identification of defects in reinforcement and/or concrete,
- the heating of the bars by the concrete cover is possible, effective and safe.

The research is an impulse for the authors to develop further ideas for the use of EC heat stimulation techniques, e.g. for the detection and identification of simulated defects in steel bars or concrete. In order to diagnose real engineering structures, it is necessary to perform verification tests of this diagnostic technique on large concrete samples with complex mesh bar systems. One more concept is to perform automated thermal stimulation and measurement based on scanning larger areas of reinforced concrete elements.

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