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APPLYING ACTIVE THERMOGRAPHY IN THE NON-DESTRUCTIVE INVESTIGATION OF HISTORICAL OBJECTS

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Abstract

The paper pertains to the problem of historic building envelope investigation with the use of active thermography. Mainly emphasized is its application in the detection of different material inclusions in historic walls. Examples of active thermography in the reflective mode application and a description of the experimental investigation has been shown on a wall model with the inclusion of materials with significantly different thermal conductivity and heat capacity, i.e. styrofoam, steel and granite. Thermograms received for every kind of envelope are compared and analyzed. Finally, the summary and conclusion is shown along with the prospects of development and practical application of this kind of investigation in historic construction.

Keywords: building envelope, historic building, material inclusions

1. INTRODUCTION

Conducting various construction works on historical objects is always connected with abiding to restrictive regulations as the methodology of the works carried out. Various studies conducted in such buildings must also minimize their effect on the analyzed elements. Non-destructive studies, which include thermographic analysis, are most often used for this purpose [3,7]. So-called passive thermography, using the natural exchange of heat between the

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analyzed object and the external environment is commonly known. However, we are often faced with the lack of possibility of conducting such studies when dealing with unheated buildings, or when we wish to conduct studies during a period when the difference between the two sides of the analyzed element does not exceed 10 K [3] – both of these situations are typical of historical objects. In such situations, active thermography, which relies on heating the analyzed element and assessing its heat response over time using the cyclical registration of thermograms after turning on the heating, can be applied. Such analysis is among non-destructive methods, involves no contact and is non-invasive. Its application may be limited by the temperature required to heat the analyzed element, which increases along with the need to penetrate deeper into the analyzed structure [2].

2. APPLICATION OF ACTIVE THERMOGRAPHY

Active thermography can be applied in the analysis of historical objects to locate and identify various kinds of material inclusions [3,6], such as: rebars and steel profiles (Fig.1a), air voids (Fig.1b), paintings and reliefs (Fig.1c), wooden load-bearing elements (Fig.1d), straw or brick filler of a half-timbered walls space (Fig.1e), or different kinds of brick rebuild (Fig.3f).

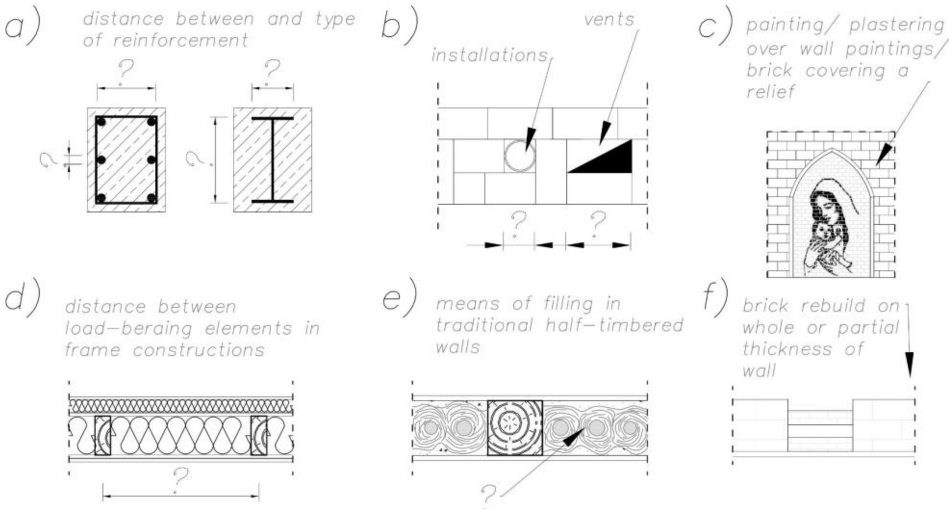

Fig. 1. Examples of applying active thermography in studies on historic buildings

Numerous brick rebuilds which remain undetectable under a layer of applied plaster are especially typical of historical buildings. Active thermography, as a non-destructive method of investigation, is an ideal solution for analyzing building partitions and their elements in buildings requiring particular care to be taken. One ought to keep in mind that the material inclusions can be divided into superficial (near the surface) or deep ones, based on their location. The first of them occur no deeper than a few cm from the surface of the analyzed element and are easier to identify. Active thermography in reflective mode (camera and source of heat stimulation are located on the same side of the partition) can be used to locate these inclusions. Such a study has been described in the present work. Deep material inclusions are more difficult to localize, requiring active thermography in transmission mode (thermographic camera and heat source located on opposite sides of the analyzed element). The deeper the inclusion, the more difficult it is to locate [1].

3. EXPERIMENTAL RESEARCH

3.1 Chosen research model

In order to confirm the thesis on the possibility of identifying various kinds of material inclusions in the historical partitions of buildings using active thermography, a case study was carried out. The study called for two models of a partition, made of oriented strand board (OSB) and drywall of respective thicknesses of 64 and 66 mm, and measuring 1250 x1250 mm and 1200 x 1250 mm respectively. Material inclusions of: steel, granite and XPS styrofoam were inserted in each of them. These inserts differ significantly enough in terms of thermal properties, i.e. the thermal conductivity coefficient and thermal capacity, to assess their influence on the level at which it is possible to identify materials in partitions.

3.2 Construction of test station and research methodology

The test station has been shown in Fig.2. Its central part contains a model of the partition with a styrofoam frame placed around it, which eliminates the heating of the back surface of the element, as well as a perpendicularly placed: infrared radiator with a power of 6 x 1kW (source of heat allows a steady stream of thermal stimulation – a type of active impulse thermography) and thermographic camera with a resolution of 320x240 with a function enabling thermograms to be taken cyclically. The experiment was divided into two main stages. The first of them involved heating the model surface with the use of a heat radiator continuously for a period of 30 minutes, whereas in the second stage thermograms of the surface being cooled were taken every 30 seconds.

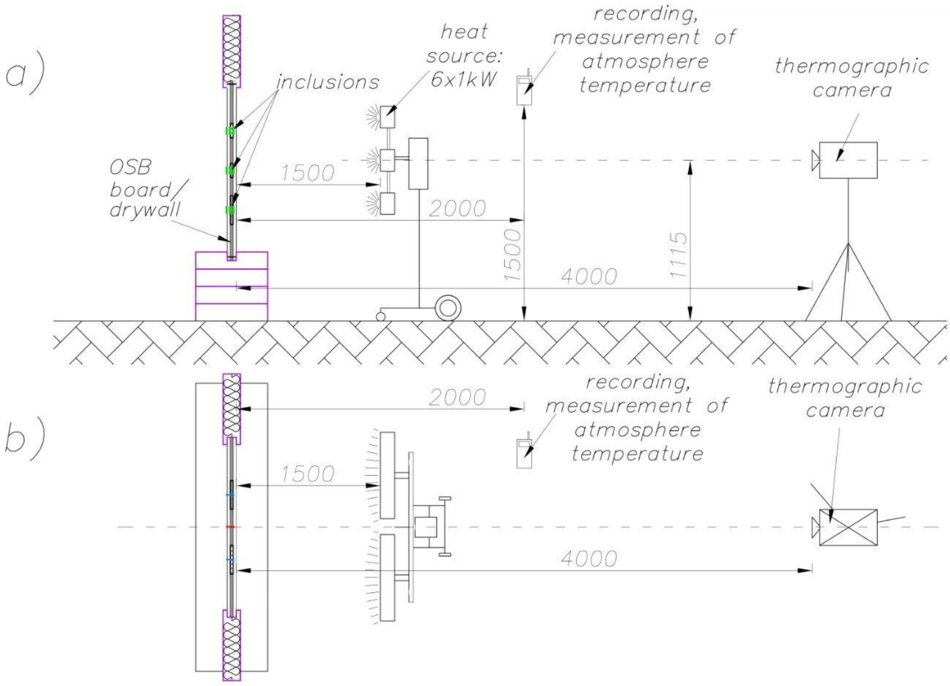

Fig. 2. Plan of test station applied in active thermography in the reflective mode

During the period of a few hours prior to the measurement being taken, during heating and during the thermographic recording, stable temperature conditions should be maintained. A description of similar studies can be found in the works [4, 5].

4. SELECTED RESEARCH RESULTS

4.1 Temperature contrasts

Most often, so-called temperature contrasts [2], [3] are used for the description of the field of temperature of the analyzed surface which changes over time. Two of the most commonly applied types have been presented below:

1) Absolute contrast (1) showing the difference between the temperature in the cross-section with the material inclusion and the homogenous cross-section.

$$C_a(t) = T_p(t) - T_{pj}(t) \tag{1}$$

where: $T_p(t)$ - temperature in any chosen point on the surface

$T_{pj}(t)$ - temperature at the surface over a homogenous area

2) Standard contrast (2) refers changes in the temperature field to the initial temperature conditions present prior to thermal stimulation.

$$C_s(t) = \frac{T_p(t) - T_p(t_0)}{T_{pj}(t) - T_{pj}(t_0)} \tag{2}$$

where: $T_p(t_0)$ - temperature prior to thermal stimulation of the analyzed surface at any given place,
$T_{pj}(t_0)$ - temperature prior to thermal stimulation at a point of the analyzed surface above a homogeneous area

Absolute contrast has been illustrated in Fig. 3, with the standard contrast in Fig. 4 for each of the cross-sections with an inclusion. The results presented in the first graph show a better possibility of detecting each of the three material inclusion in the model made of drywall. The absolute contrasts for drywall are nearly 1^{o}C, approx. 0.6^{o}C and 0.4^{o}C higher for XPS Styrofoam, steel and granite, respectively, when compared to those of the OSB board model.

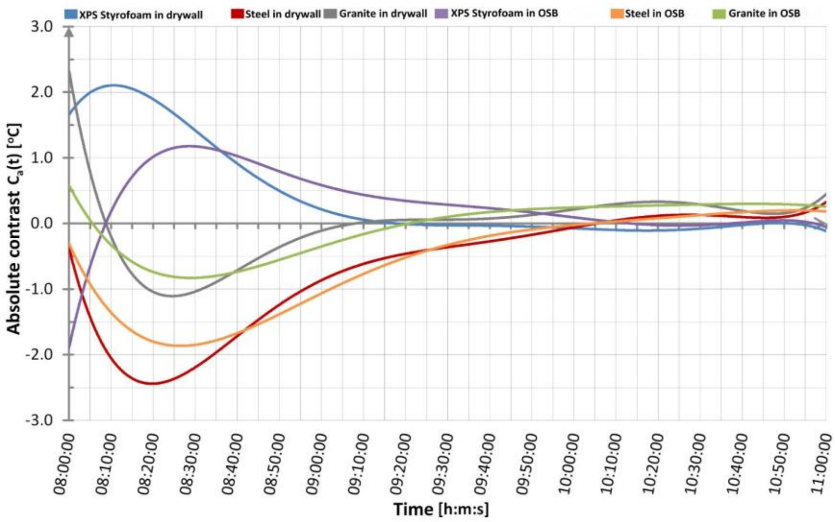

Fig. 3. Values of absolute contrast during the cooling of the analyzed surface (description in text)

It can additionally be observed that in the model of the wall made from drywall, the maximum values of the contrast are reached much faster than in the model made from OSB board. The XPS Styrofoam inclusion is best visible (highest absolute contrast) as soon as after approximately 10 minutes from the moment the cooling of the element was initiated, the steel inclusion after approximately

20 min., whereas granite – after approximately 25 minutes. These times are approximately 20 minutes longer for the model of OSB boards in the case of XPS Styrofoam, 7 minutes for steel and 5 minutes for granite. It is important to note that a positive absolute contrast means that the areas on the thermograms are visible as areas with a higher temperature than that of the homogenous area, whereas a negative value of contrast indicates areas which are "cooler" than the homogenous cross-section. Additional information provided by the graph are the so-called reverse contrasts, visible after approx. 2.5 hours from the moment cooling is initiated. They are characterized by a change of sign at the value of absolute contrast, which means that after this time, areas in the cross-section with the XPS Styrofoam inclusion are depicted as “cooler” areas, whereas cross-sections with granite and steel as “warmer” areas than the homogenous cross-section without inclusion. Along with the cooling time of the element being extended, all contrasts strive to achieve a value of zero, which is equivalent to achieving thermal balance of the analyzed partition model with the environment (lack of heat flow). In order to illustrate the dynamics of temperature changes taking place on the surface of the analyzed element in relation to the initial conditions existing on the surface, standard contrast was used (Fig. 4).

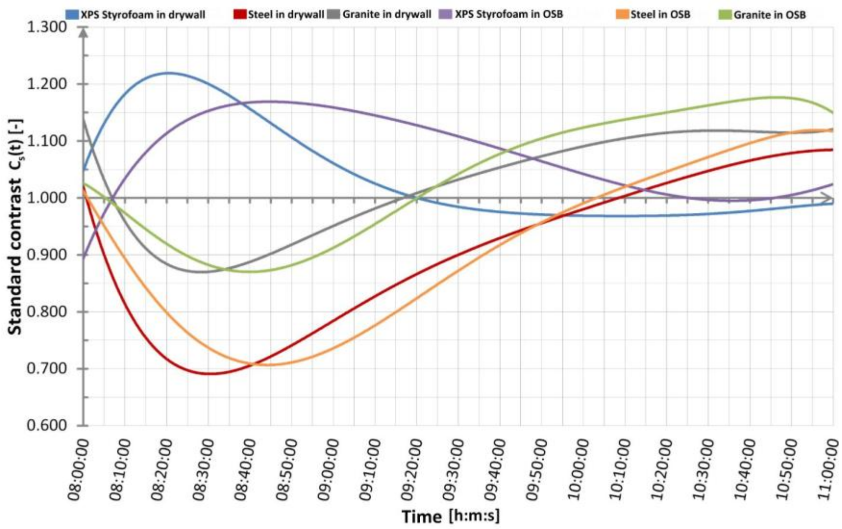

Fig. 4. The value of standard contrast during the cooling of the analyzed surface (description in text)

The scheme of variation for values of standard contrast is similar to that of absolute contrast. A value of 1.0 on the graph characterizes a state when the homogenous cross-section as well as the cross-section with the inclusion cool in an evenly manner. Values above 1.0 signify that the given cross-section cools slower than a homogenous one, whereas those under 1.0 indicate the increased cooling of the cross-section with the inclusion. Values shown in Fig. 4 can be directly connected with the thermal capacity (C) of the given cross-sections as well as the values of their thermal resistance. The higher the thermal capacity and lower the thermal resistance, the faster the heat applied to a given cross-section "passes through" to the other side. For the cross-section with the XPS Styrofoam inclusion, thermal resistance behind the inclusion was 2.5 times higher than when compared to the thermal resistance on the surface before the inclusion, whereas for steel and granite inclusions, it remains basically the same. A reflection of the described situation can be seen in the form of standard contrast with values exceeding 1.2 for Styrofoam ("stopping" the flow of heat in the cross-section) as well as for steel and granite, where the values of contrast equal below 0.7 and approx. 0.87 respectively ("escaping" of heat to the other side of the barrier).

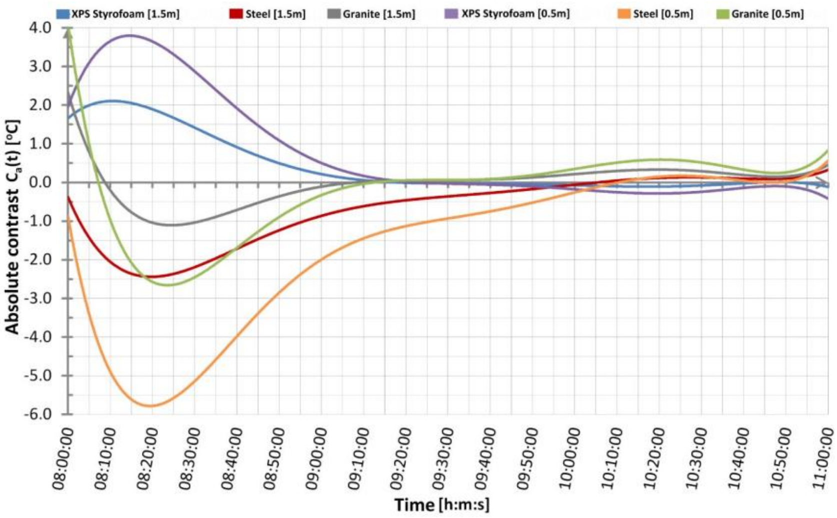

Fig. 5. Differences absolute contrast at two different levels of heating the surface (temperatures provided in the legend)

In the case of historical objects and the potential application of active thermography in the analysis of partitions in such objects, the temperature to which the surface ought to be heated in order to be able to locate the material inclusions found within is a very important issue. One ought to remember that the deeper the inclusion lies and the more similar its thermal properties are to the material in which it is found, the more difficult it is to locate such a partition with an inclusion. As a consequence, higher temperatures of heating the analyzed element ought to be applied. The influence of the level at which the surface is heated on the possibilities of locating material inclusions has been presented in Fig. 5. The drywall model was heated at a distance of 0.5 m as well as 1.5 m for 30 minutes, which in consequence allowed the element to be heated to the respective temperatures of 90^{o}C and 50^{o}C. Absolute contrasts shown in Fig. 5 indicate a difference of over 3^{o}C for steel and approx. 2^{o}C for granite and XPS Styrofoam. This difference can have a significant influence when attempting to solve inverse equations of thermal conductivity. However, for the initial location of inclusions in historical partitions, it is sufficient to heat them to a temperature of approx. 50^{o}C (for surface inclusions located under a, e.g. 20-30 mm layer of plaster). All surface temperature readings were taken as the average values of rectangular areas with a surface area of 100 x 50 mm (half the size of the inclusions).

4.2 Thermograms

The most important in the detection of material inclusions in building partitions are, of course, thermograms. It is on their basis that areas in which disturbances in the temperature field on the surface can be located and conclusions regarding the possibility of the presence of inclusions of materials other than the homogenous material of the partition can be drawn.

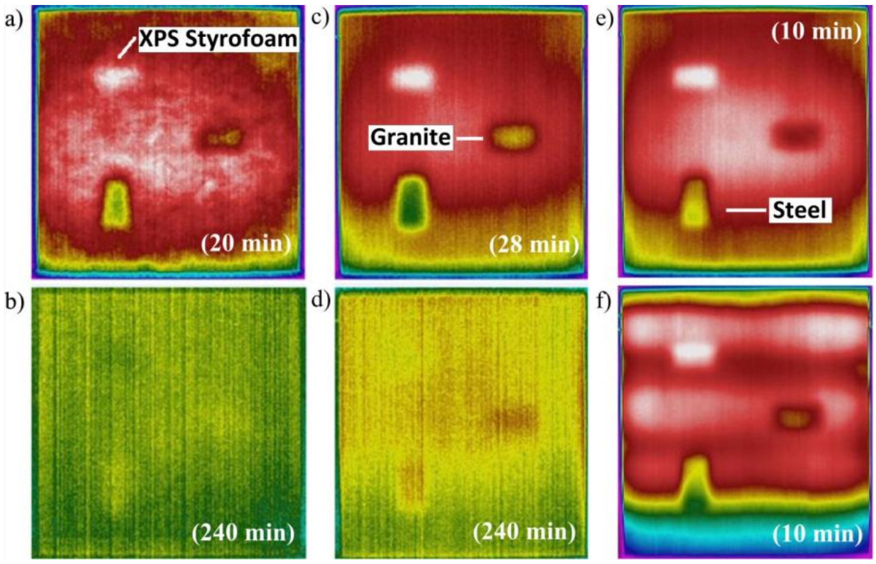

Fig. 6. Thermograms for models of OSB board (a, b), drywall (c, d), and various degrees of heating the surface (e, f); the time from when the heat source was turned off has been provided in the brackets

Figure 6 reveals the distribution of the temperature field at characteristic moments of the measurement carried out. As noticeable, the most visible inclusion is the one of steel (highest value of thermal conductivity coefficient). The remaining inserts can also be easily localized on the thermograms. In Fig. 6e and 6f, the difference in the location of inclusions in relation to the initial temperature to which the element was heated has been shown. As can be observed, it was enough to heat the element to a temperature of 50^{o}C (Fig. 6e) in order to determine the location of partitions with inclusions. Heating to high temperatures (90^{o}C - Fig. 6f) required the heat emitter to be placed closer to the analyzed element which, in consequence, resulted in the uneven heating of the surface, observed in the form of three horizontal strips which were heated a bit more than the remaining part of the element.

5. SUMMARY AND CONCLUSIONS

Based on the conducted research experiment and analysis of the research problem, the following conclusions can be drawn:

1) The best temperature contrasts in the analyzed model of the partition occur within 10 to 30 min after the cooling of the element has been initiated.
2) After approximately 140 minutes, a second moment when areas with inclusions in the partition can be located occurs, with inclusions characterized by an inverse contrast.
3) It is not necessary to heat surfaces to high temperatures to locate inclusions in partitions. In the case of the model partition (locating inclusions up to approximately 20-30 mm beneath the surface of plasters and wood finishes), values of approx. 50^{o}C are sufficient.
4) When assessing partitions, it is very important to heat the surface of the analyzed element evenly in order to eliminate unnecessary disturbances in the temperature field, making it more difficult to locate inclusions.

The use of active thermography can facilitate the easier identification and analysis of building partitions in historical buildings, in the case of which it is not possible to apply other research methods.

In addition to the mere location of material inclusions, it is important to identify their thermal properties and depth at which they lie. These characteristics pertain directly to solving the reverse equation of heat conductivity. A following step in the authors' research will be an attempt to solve the above problem and carry out case studies on actual buildings.

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ZASTOSOWANIE TERMOWIZJI AKTYWNEJ DO BADAŃ NIENISZCZĄCYCH OBIEKTÓW ZABYTKOWYCH

S t r e s z c z e n i e

Artykuł porusza zagadnienie wykorzystania termografii aktywnej w nieniszczących badaniach przegród budowlanych w obiektach zabytkowych. Opisane zostały potencjalne możliwości stosowania badań, takie jak: lokalizacja rodzaju zbrojenia w elementach żelbetowych, detekcja pustek powietrznych i przemurowań w przegrodach, określanie rodzaju struktury materiałowej zabytkowej przegrody lub identyfikacja ukrytych pod wartwą tynku lub farby malowideł ściennych. W pracy opisano przebieg doświadczenia z wykorzystaniem termografii aktywnej w trybie odbiciowym. W badanych modelach przegród, wewnętrzne wtrącenia materiałowe zostały wykonane ze styropianu XPS, stali oraz granitu. Otrzymane wyniki opisano za pomocą kontrastów temperaturowych (absolutny i standardowy) oraz zinterptretowano otrzymane termogramy. W podsumowaniu przedstawiono wnioski z przeprowadzonego doświadczenia. W artykule potwierdzono przydatność nieniszczących badań za pomocą termowizji aktywnej do detekcji przypowierzchniowych wtrąceń materiałowych.

Słowa kluczowe: przegroda budowlana, obiekty zabytkowe, wtrącenia materiałowe

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