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Assessment of Internal Damages in Sandwich Panels via Active Thermography

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Recently, the application of polymer-based composites in civil constructions and substitution of traditional materials by composites became a normal practice. Increasing applicability of composites, primarily sandwiches with soft cores, induces the development of the non-destructive testing methods used for the quality control and in-service inspection of the constructions made of such materials. In this study the internal damages, typical for the foam-core thick sandwich panels, that occur during manufacturing process as well as during in-service life were investigated. The description of internal damages was prepared based on real practical cases. Several types of damages were simulated in the foam-core sandwich panels, which were then tested using active thermography. Obtained results point to the great potential of this method in application for the damage assessment of structures and constructions made of these materials. The damages like cracks, partial local lacks of the core and debonding were successfully detected and localized. The method can be applied during inspections of civil structures being currently in operation and as a quality control method during manufacturing of these structures.

Key words: foam-core sandwich panels, internal damages, active thermography, quality control.

1. Introduction

Sandwich structures made up of two external, stiff and very thin faces (metallic, plastic or composite) separated by a lightweight core are widely used in many areas of engineering. This is due to their several attractive features like high load-bearing capacity coupled with low weight (this is caused by the separation of the skins by the core increases the moment of inertia of the panel with small increase in weight), good thermal insulation, low cost of production and easy assembling. The most common core materials are the different kinds of cellular solids like metallic, glass, ceramic and polymer foams [1]. For engineering purposes, foams passess a unique set of features such as high energy absorption capacity [2], acoustic and thermal insulating properties and homogeneous core which make these materials very popular in aircraft and naval industry, automotive and civil engineering or packing [3]. When using porous materials in structural applications, the knowledge of their integrity and behaviour is needed because the failure due to internal defects in the core material or the entire element can lead to abnormal functioning of layered structures [4, 5]. The possible defects types can be roughly divided into two categories: manufacturing flaws and in-service damage. The most common production flaw, which has been linked to sandwich structures since the beginning, is lack of bond between the core and faces [6–8]. This invisible defect may initiate delamination process, it may reduce the established load capacity or cause other unpredictable phenomena, e.g., blisters. The last ones appear in sandwich plates with specific gas-realising core materials and is associated with chemical degradation within the core due to the action of temperature. Internal gases looking for the weakest part of the structure or connection between layers to come out in the form of external facing bulge that causes debonding of layers. The next defect is a local lack of the core material. This one may be associated with errors at production stage (voids, porosity) or damages that occurred during operation stage. The latter defects discussed in this paper are cracks and core crushing being a result of impact, local indentation and/or excessive through thickness loading. These types of defects can result in localized debonding and a lack of support for the sandwich facing, leading to potential failure of the entire sandwich panel.

In order to ensure the structure integrity and prevent the structure damages from the deterioration, structural health monitoring (SHM) has become more and more important [9] and caused the increased interest in developing the novel techniques for inspection. Therefore, advanced non-destructive testing (NDT) techniques are required and have been widely studied by many researchers in order to develop various types of methods such as: ultrasound (pulse-echo and through-transmission modes, water- and air-coupled, hand-held and automated scanning) [10], microwave [11], vibration-based methods [12], thermography [13, 14] and X-ray real-time imaging and backscatter scanning [15]. Selection of an appropriate NDT method for a particular application depends on many parameters such as: environment, in which the inspection has to be carried out, the purpose of inspection, the extent of the area to be inspected, the type and size of defect or damage that is suspected, the nature of the sandwich surface (flat, curved or uneven), whether equipment of a given type and the necessary personnel are available, and at what cost. Therefore, the choice of the suitable method for defects detection is not easy and evident especially for such complex and varied structures like sandwich panels.

All of mentioned NDT methods are applicable in sandwich structures but related rather with aircraft or military industry. In the following work sandwich panel with a polyurethane core used in civil engineering is studied. Analysed plate is characterized by significantly greater thickness of the core (60 to even 250 mm) compared to the panels mentioned above and presented in the cited papers. This parameter has huge influence on mechanical response of the plate and it is very hard to find any information on the application of NDT methods for such structures. Hence, in the following study the main attention is focused on recognizing the problem of defects' location and identification in thick foam-core sandwich panels using active infrared thermography (IRT). Obtained results point a to the effectiveness of this approach, which leads to the further applications during in-service inspections of such constructions.

2. Problem overview and research motivation

In this work main attention was given to location and identification of defects in sandwich plates with thick and soft core. These structures are characterised by completely different mechanical behaviour and failure modes compared to homogeneous structures. One of the most common and problematic damages occurring during manufacturing process as well as during in-service life is delamination. It is very difficult to observe this phenomenon in real structures being in operation because it is invisible on their surface (it appears inside structures). However, many laboratory tests were carried out and effect of delamination appeared in many cases. This phenomenon can have various types depending on action force (bending, shear, pressure) and type of materials of particular layers, what is presented in Fig. 1. Debonding and delamination cases presented in

a) b) c)

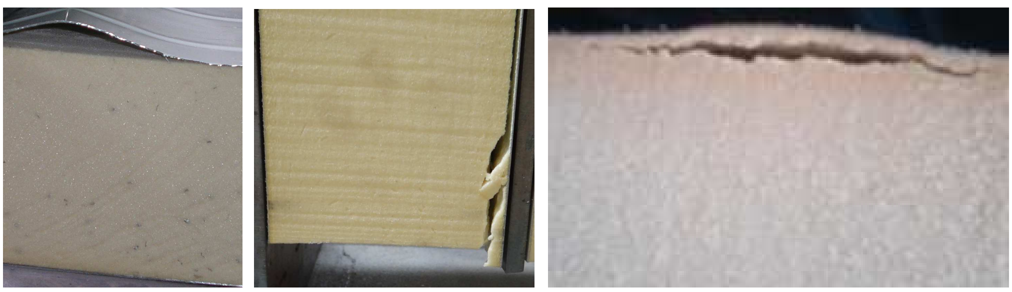

Fig. 1. Various types of delamination caused by: a) bending force, b) shear force, c) pressure.

Fig. 1 are typical for the operation conditions of foam-core sandwich panels in civil engineering. These defects are similar to phenomenon of local lacks of an adhesive, which were analysed by the authors.

The next defect is associated with a core material failure and it is caused by the shear force. Two typical laboratory tests, namely four-point bending test (currently the most common) and direct shear test, were carried out and cracks, which is shown in Fig. 2, appeared. These damages occur during operation of sandwich panels and also cannot be detected without an application of NDT methods, which allow the inspection of internal structure of them.

a) b) c)

Fig. 2. Cracks obtained during: a) four point bending test, b), c) double lap shear test.

The defects typical for foam-core sandwich composites only are the blisters. It happens that blisters appear in sandwich panels with a foam core and metal facings used in civil engineering, but very often in a temporary form (they disappear during changes of environmental conditions) and damages of the structure become invisible. Unfortunately, the failure effects can occur in the interface area and can be dangerous for further in-service life – local failure is very often the weakest point of the plate and can initiate the damage of the whole structure. The blisters produced artificially were shown in Figs. 3a, 3b. Specimens with aluminium facing on the one side and metal facing on the other

a) b) c)

Fig. 3. a) blister, b) blister with damaged face sheet, c) visible core after removing the blister.

were tested. During laboratory test pressure was introduced inside the sample. Damages caused by blisters can take different forms and locations as presented in Figs. 2c, 3.

Considering the above-described damages characteristic for the foam-core sandwich structures used in civil engineering it is necessary to find an appropriate NDT method, which is sensitive to all mentioned types of internal damages. The main goal of this study is to provide an effective tool for the detection and localization of internal damages in such structures with possibly high precision and in possibly early stages of development of the damages. From the great variety of NDT methods described above an active IRT seems to be the most appropriate method, while taking into consideration the fact that the measurements can be performed in almost arbitrary environments typical for the application of such structures. Active IRT already found wide application in the inspection of structures of civil and mechanical elements, but there are only few described studies when this approach was used in detection and localization of internal damages in civil sandwich structures. In order to investigate the detectability of the damages typical for the analysed structures they were simulated in the tested specimens.

3. Materials and testing procedure

3.1. Specimens preparation

The analysed panels of spatial dimensions of 300×300 mm consisted of a polyurethane core (manufactured by Ruukki Construction Polska Sp. z o.o.) and glass-epoxy composite face sheets (manufactured by Izo-Erg S.A.) bonded by a two-component polyurethane adhesive Macroplast U.K. 8309 and Macropur U.R. 521 (hardener) mixed in a ratio of 5 to 1. The foam has a closed-cell structure, approximately 40 kg/m^3 density and a thickness of 57 mm. It is manufacured during polymerization reaction from ingredients such as: polyol, isocyanates, catalysts and blowing gases. A total thickness of tested specimens is 58 mm.

The following damage types were considered: through-the-thickness cracks of the core, local partial lacks of the core and local lacks of an adhesive. All flawed specimens were prepared by the authors in the laboratory in artificial way: first specimen – cracks were introduced by the cutting of the entire thickness of the core plate in two orthogonal directions; second and third specimens represented local partial lacks of the core with spatial dimensions of 50×50 mm, a depth of the removed material are 1/4 and 1/2 total thickness of the sample and located in their centres; fourth specimen represented local lacks of an adhesive (location and dimensions are the same as for second and third specimens). The introduced damages allowed to simulate the real damages that occurred during operation of the investigated structures described in Sec. 2.

3.2. Experimental setup description

Active thermography approach in NDT problems is often used as an effective tool for detection and localization of both external and internal structural damages. A good overview of active thermography methods applied for non-destructive evaluation of honeycomb-core sandwiches was presented in [13]. From the variety of active thermography approaches the authors decided to choose the pulse thermography method due to its simplicity in application and comparatively good sensitivity to the internal damages. The principle of this method is as follows. The tested structure is thermally excited by the heating pulse (usually by halogen or xenon flash lamps, but sometimes using ultrasound or eddy current excitation). The surface of the tested structure is monitored by the infrared camera, which registers a thermal response of a structure after thermal excitation. Due to the differences in thermomechanical properties of the tested structure in the damaged area (e.g., the differences in coefficient of thermal conductivity) the difference in temperature gradient in such area with respect to undamaged ones is observed. A thermal response is usually registered as single image or a sequence of thermographic images.

In order to ensure a good emissivity of surfaces of tested plates they were covered by black matt paint. The tests were performed using VarioCAM hr infrared camera, which was placed at the distance of 0.8 m from the tested specimens. The emissivity was defined as 0.9. The ambient temperature was measured and then set to 24°C. The heating pulse was induced by two 1000 W halogen lamps located on the opposite sides with respect to infrared camera on the aluminium frame and directed onto the surfaces of tested panels. A view of the experimental setup is presented in Fig. 4.

Fig. 4. Experimental setup.

The measurements were carried out as follows. The halogen lamps were switched on for 2 seconds and after this time the registration of a thermal response was performed. For each of the tested panels a sequence of the infrared images was registered using IR camera-dedicated software IRBIS. Some selected images from the sequence of one of the tested panels are presented in Fig. 5.

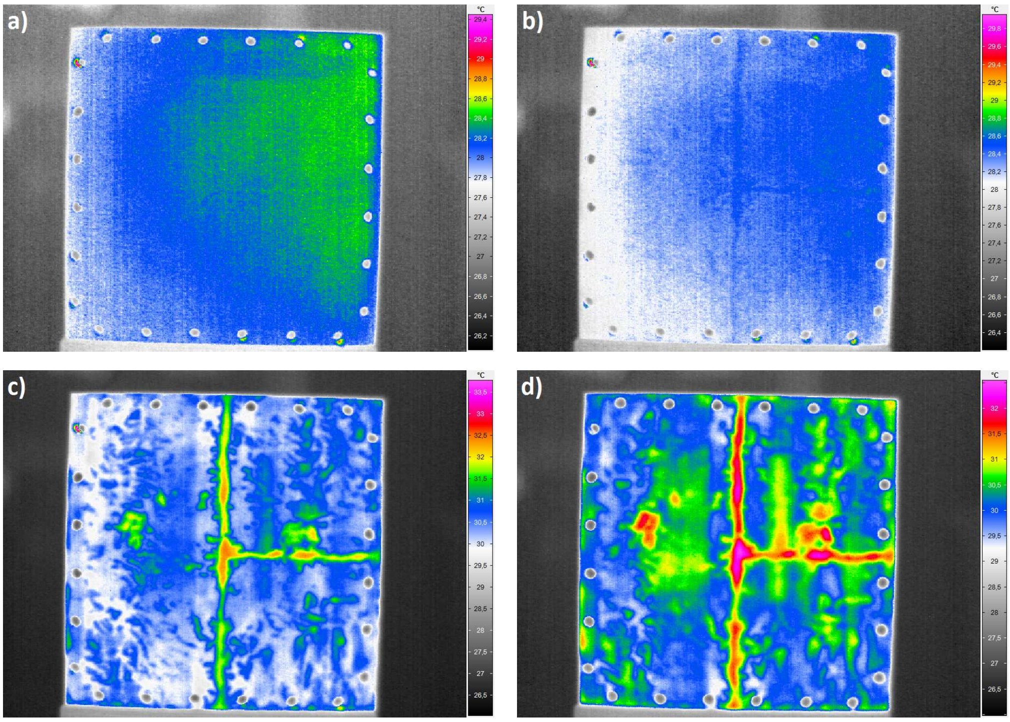

FIG. 5. Exemplary thermograms obtained during the experiment: a) before excitation, b) during excitation, c) 4 s after excitation, d) 10 s after excitation.

One can observe that the selection of appropriate time after thermal excitation is important during the damage assessment procedure. In Fig. 5a the damages are not yet visible. When the thermal excitation is applied to the surface of a tested panel (see Fig. 5b) the damage became visible, however the image is unclear and the evaluation of damage shape and position is not possible at this stage. After thermal excitation the damage is clearly detected and localized (Fig. 5c). However, if the time after excitation is longer (Fig. 5d) the temperature distribution on the surface of a tested structure become more irregular due to the convection and tending to thermal equilibrium, which results in blurring of the damaged regions and makes the decision about structural condition more difficult.

4. Results and discussion

Since the damaged regions have greater thermal conductivity than undamaged ones the increase of temperature in these regions is greater. Obtained thermograms for the analysed panels are presented in Fig. 6. Following the results of preliminary analysis presented in Sec. 3 for all of the tested panels the time of 4 s after thermal excitation was chosen as the relevant one.

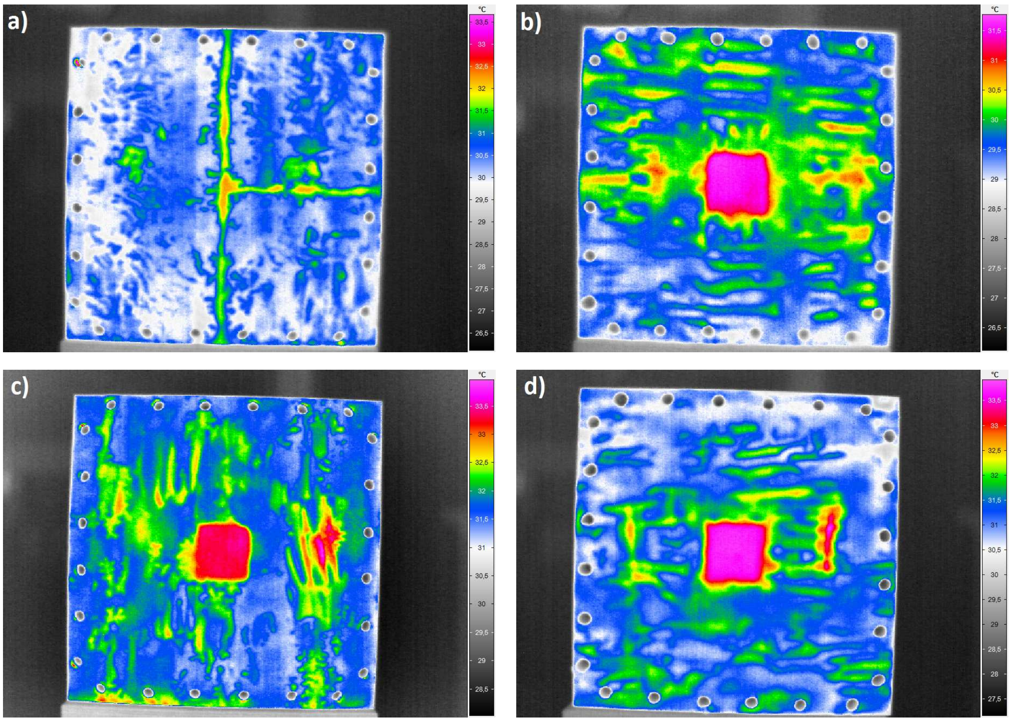

Fig. 6. Thermograms for a) cracked core, b) 1/2 local lack of a core, c) 1/4 local lack of a core, d) local lacks of an adhesive.

One can observe that the damages in all investigated cases are clearly detected and localized. The temperature of damaged regions is significantly higher than for other regions of tested panels and the contours of damages are accurate. However, among the damaged regions, the remaining area with specific temperature distribution are observed. The locally increased temperature is caused by the inappropriate bonding of face sheets to the core of a sandwich panel or local surpluses of a glue, which was caused by the manual gluing of the face sheets. The thermographic analysis can detect and localize such manufacturing imperfections as well, which can be applied during quality control procedures of such panels.

The disadvantage of the active thermography is that the depth of a damage cannot be determined, i.e., in the investigated cases (cf. Figs. 6b–6d) the damages remain undistinguishable. However, the presented approach allows for detection and localization of the damages, which are located under the face sheets. This has a practical importance in the inspection of civil structures. The cracks of the core material that occur mainly during operation of these structures are well recognizable. The debonding between the face sheet and the core has similar physical nature as blisters occurring due to the chemical reactions on the interface. As presented in Fig. 6d such damages are well detectible using this approach. The partial lacks of the core or sudden changes in the thickness of the core, which can occur as errors during manufacturing process are also well detectable. Although pulse thermography has numerous disadvantages with respect to other approaches in active thermography (e.g., lock-in thermography or vibrothermography) such as nonuniform excitation, reflections, etc. [13], this method is still the easiest in application and fast. Considering the area of applications of such NDT procedures in civil engineering and effectiveness of damage evaluation confirmed in presented studies this approach seems to be the most reliable one.

5. Conclusions

In the present study the evaluation of applicability of active thermography for the detection and localization of internal damages in foam-based thick sandwich structures used in civil engineering was performed. The typical damages for such structures were defined and briefly described. Based on this the damages in sandwich panels were simulated in the artificial way and covered all mentioned types of imperfections that occur during their manufacturing and operation. The tests were performed using pulse heating of structures and registration of their thermal response was recorded by infrared camera. Obtained results show good ability of detection and localization of all considered damages, however the method does not reveal the distinguishability of various types of damages. Nevertheless, the results of presented study confirm that the method can be successfully applied for the inspection of the sandwich civil constructions being in operation.

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