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EXPERIMENTAL INVESTIGATION OF DEFECTS INFLUENCE ON COMPOSITES SANDWICH PANELS STRENGTH USING DIGITAL IMAGE CORRELATION AND INFRARED THERMOGRAPHY METHODS

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ABSTRACT

The article is devoted to the experimental investigation of the defects' influence on the residual strength of composites structure, as well as the possibility of using local repair operations.

The objects of the research are structurally similar elements of acoustical sandwich panels (ASP) after a local repair of defects, such as a through breakdown. The specimens were produced by the serial technology from a fiberglass prepreg.

The research was carried out using a universal electromechanical system Instron 5982 and servo-hydraulic system Instron 8801. For the analysis of the stress-strain state of the deformable elements, the authors used the non-contact three-dimensional digital optical system Vic-3D, the mathematical apparatus which is based on the method of digital image correlation (DIC). To control the internal geometry of the specimen and assess possible defects, the inspection infrared thermal imaging system FLIR SC7000 was used. The techniques of a joint use of testing and measuring systems under static and cyclic tests were offered.

For comparison, the repaired sandwich panel specimens were tested under tension and tension under a preliminary cyclic loading with the registration of the deformation fields and thermal images. Their deformation and fracture mechanisms are analyzed, and their loading diagrams are obtained. The experimental data were obtained from the Vic3d system study of the evolution inhomogeneous fields of axial and transverse deformation on the surface of repaired sandwich panels under static loading and cyclic tests. By using the infrared thermal imaging system of the internal structure, the processes of the defects development and the temperature distribution on the surface of the test specimen were detected.

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Introduction

The use of composites can reduce a structure's weight, as well as retain or improve its mechanical characteristics. Composite materials are widely used in aerospace engineering for samples subject to variable loads [1]. During the operations of structures made from composites, it is inevitable that different defects occur; meanwhile it is becoming more and more relevant to study the options of the local repairs of structures in field operations.

The research is targeted at studying the structurally similar elements of acoustical sandwich panels (ASP) with an applied defect, such as a through breakdown, after local repairs. The through breakdown of the cover is characterized with a damage of all the reinforcement layers of a sample, which takes place during operations. The local repair approach includes the removal and layerwise replacement of damaged material's layers by the repair materials by keeping the base direction, as well as by adding two extra layers on top of the repair layers, at both sides of the specimen. The damaged filler is not restored, it is filled with a special composition. Details of the repair technologies and methods of mechanical testing of ASP are given in [2-5].

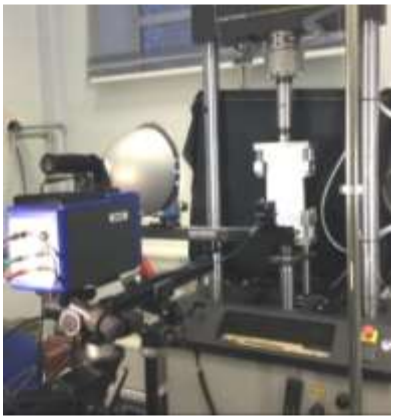
The studies related to cyclic loading, predicting the remaining operation life, the initiation and distribution of fatigue cracks are among crucial problems now. The method of infrared thermography is widely used, when conducting mechanical researches aimed at receiving detailed information about the principles of energy accumulation during the process of metals deformation [6-10]. Previously the researches with thermography were carried out for homogeneous materials, but new technologies and advanced equipment made it possible to use this method for composites as well [11-13].

More detailed studies of the behavior of composites under cyclic loading using the traditional methods and approaches are not sufficient. To study defects, cracks, delaminations, it is most common to use such methods as ultrasonic flaw detection, X-ray, thermography, acoustic emission and optical method of correlation of digital images. A combined use of the above methods is a promising area in experimental mechanics. The works in [14-18] show that it is possible to use acoustic emission, infrared imaging and contactless optical systems of analyzing deformation fields for different types of tests.

1. Methods of Experimental Studies

The experimental studies were carried out at the Center for Experimental Mechanics of Perm National Research Polytechnic University. The research program included the mechanical tensile testing of ASP specimens sized 150×350 mm, based on the previously proposed methods [3, 4, 19, 20] under static and cyclic loadings using the contactless optical vision-based system Vic-3D and infrared imaging system FLIR to control the internal structure of the specimen, including the repaired zone (Fig. 1).The defect is located in the central part of the ASP specimen. In order to conduct the researches, we chose the most complicated type of defects, which is most difficult to repair, i.e. the through breakdown of the structure. The defect size was chosen based on the calculation that the defect length was equal to one-half of the ASP specimen's width (l = 70 mm). To reduce the concentration of stresses at the edges of the defects, a radius of R = 7,5 mm was chosen.

a



b

Fig. 1. ASP specimens during the testing in the electromechanic system Instron 5982 under static tension (*a*) and in the servohydraulic system Instron 8801 during cyclic testing (b)

The static studies were carried out using a universal electromechanic system Instron 5982. This machine is designed for quasistatic testing under tension, compression, bending with the load of up to 100 kN and the loading rate from 0,001 to 500 mm/min. A more detailed description is given in [5, 21]. The preparation of the tests consisted in setting the parameters of the test and measuring equipment using the specialized software, synchronizing the test machine with the video system and the thermal imager, preparing and installing the specimen.

The following testing parameters were set: motion speed of the mobile traverse under stretching was 5 mm/min; the shooting speed was 15 frames per second; the main parameters of the correlation processing were: the local region (subset) was 59×59 pixel, the step was 4 pixel (subset 59, step 4); the shooting speed of the infrared imaging system was 100 Hz.

The digital image correlation method (DIC) is an effective non-contact method for measuring deformations on the surface of objects under study by comparing digital images taken during loading [22]. Initially, the displacement fields are constructed, then the deformation components are calculated. With the help of the DIC method, it is possible to analyze the change of deformation fields, according to the contrast relief of the specimen, and also estimate the degree of deformation, the moment and place of its localization at the macrolevel. To analyze the displacement fields using DIC method, it is necessary to prepare the surface of the test specimens [22-24], so a contrast fine-dispersed surface is applied, then the specimen is fixed in a special test rig (Fig. 1).

Before testing, in order to control the inner structure of the specimen and the "healed" defect, the thermal flaw detection had been made, i.e. the tested specimen was heated using the incandescent electric lamp of 150 W for 30 seconds, the heating was at a distance of 0.15 m. Fig. 2 shows the thermal images of the specimen before and after the heating in an unloaded condition. In order to control temperature, a diagram was built on the destribution of temperatures according to selected lines, which go through the geometric centre spot on the specimen's surface (Fig. 2, *b*) after heating at the time, when the incandescent electric lamp (Fig. 2, *c*) is switched off, the maximum temperatures on the specimen's surface are less than 40º C. Such a mode of a short-term heating is chosen in such a way, that the increased temperature would not affect the mechanical properties of the adhesive layer in the repair zone. The experimental data in [21] also indicate that a short-term increase of temperature up to 40 ºC will not affect the mechanical properties of fiberglass and the adhesive layer, in particular.

The fatigue tests were carried out using the servohydraulic testing system Instron 8801. This system is focused on static tensile tests, compression and bending with the maximum load of 100 kN, fatigue testing with a different waveform and the frequency up to 30 Hz, the testing with an arbitrarily set law of kinematic, static or mixed mode of loading. The parameters of cyclic tests were chosen based on the standards of the contingency factor for aviation composites, i.e. 2-2,5. The data gained during the ASP specimen testing without defects introduced in [2] were chosen as reference values. During the implementation of the cyclic tests we used the alternating-sign nonsymmetric cycle of force loading with the following parameters: skewness ratio R = –0,25; amplitude of cycle N_a = 25 kN; a sine wave form; frequency 0,25 Hz; the number of cycles n = 200. Wheras the minumum values of loading were 10 kN, the maximum were 40 kN.

The tests were carried out in two stages, each step was 100 cycles. At the first stage, after each 10 cycles, a stop was made at the peak of the maximum to register the deformation fields and temperatures in order to analyze the dependence of the development of local damages and defects on the number of loading cycles.

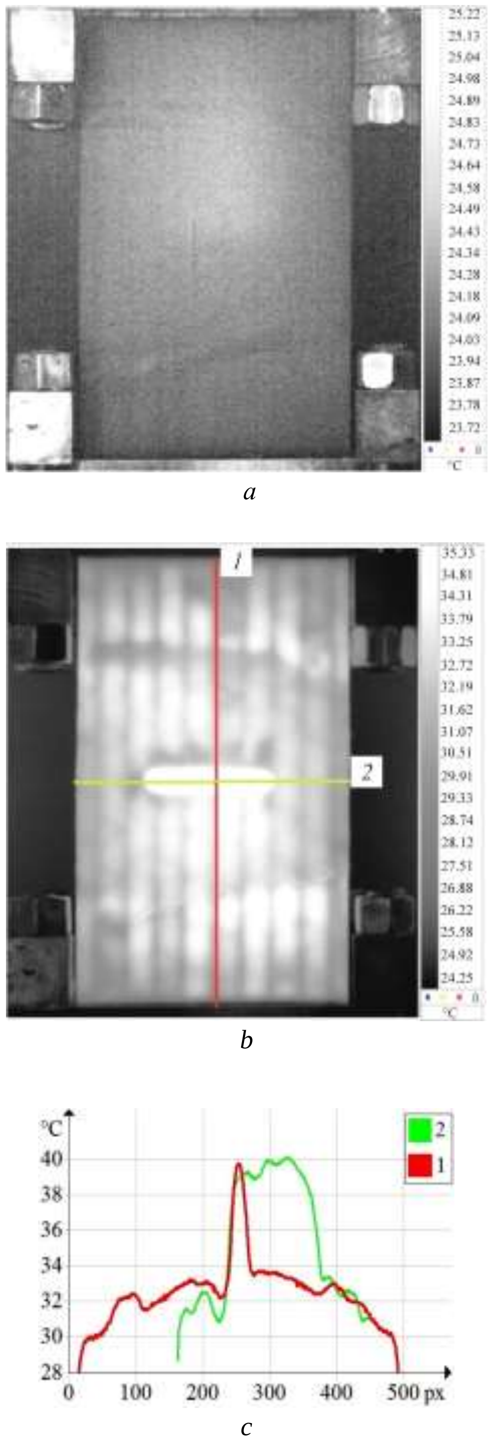


Fig. 2. The thermal images of the ASP specimen with a "healed" defect before (*a*) and after (*b*) heating, and the diagram of temperature distributions, according to the selected lines on the specimen's surface after heating (*c*)

At the second stage, also after each 10 cycles, a stop was made at the peak of the maximum, then the ASP specimen's repair zone was heated (similar to the mode described above), and the registration of the internal structure was made.

After the cyclic testing program, the ASP specimen was subject to static loading until it was fractured.

2. Testing results

During the static tensile test, the diagram of loading (Fig. 3), fields of transverse and longitudinal deformations until the separation of the repaired layer at the moment of the primary fracture (point 2, Fig. 3) were built, as the vision-based system allows to get deformation fields on the surface of the studied object and their corresponding thermal images (Fig. 4).

The loading diagram is built based on the data from the video system using the virtual extensometer [3, 24], while only displacements in the operation zone of the specimen were considered.

At the region of the load curve 1-2, the images of deformation fields and thermal images are identical and correspond to Fig.4. When reaching point 2 of the curve, there came a primary destruction, which was accompanied with a crack and characterized with a local delamination of the repair zone (Fig. 4, *b*). Later at the 2-3 domain there was a full-width delamination of the repair zone of the specimen, which was obvious, according to the thermal image (Fig. 4, *c*), the destruction of the adhesive layer of the pressure shell with a tubular filler and a subsequent local loss of stability of the pressure shell.

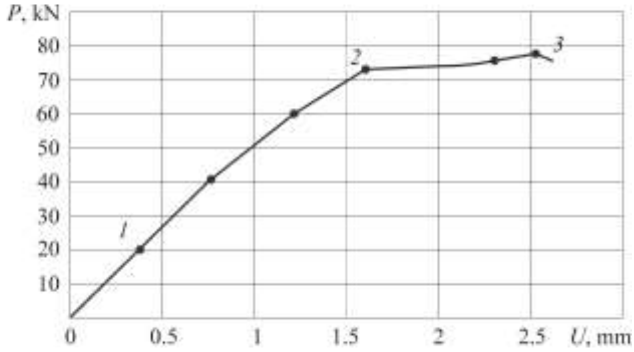


Fig. 3. Loading diagram of the ASP specimen under tensile test

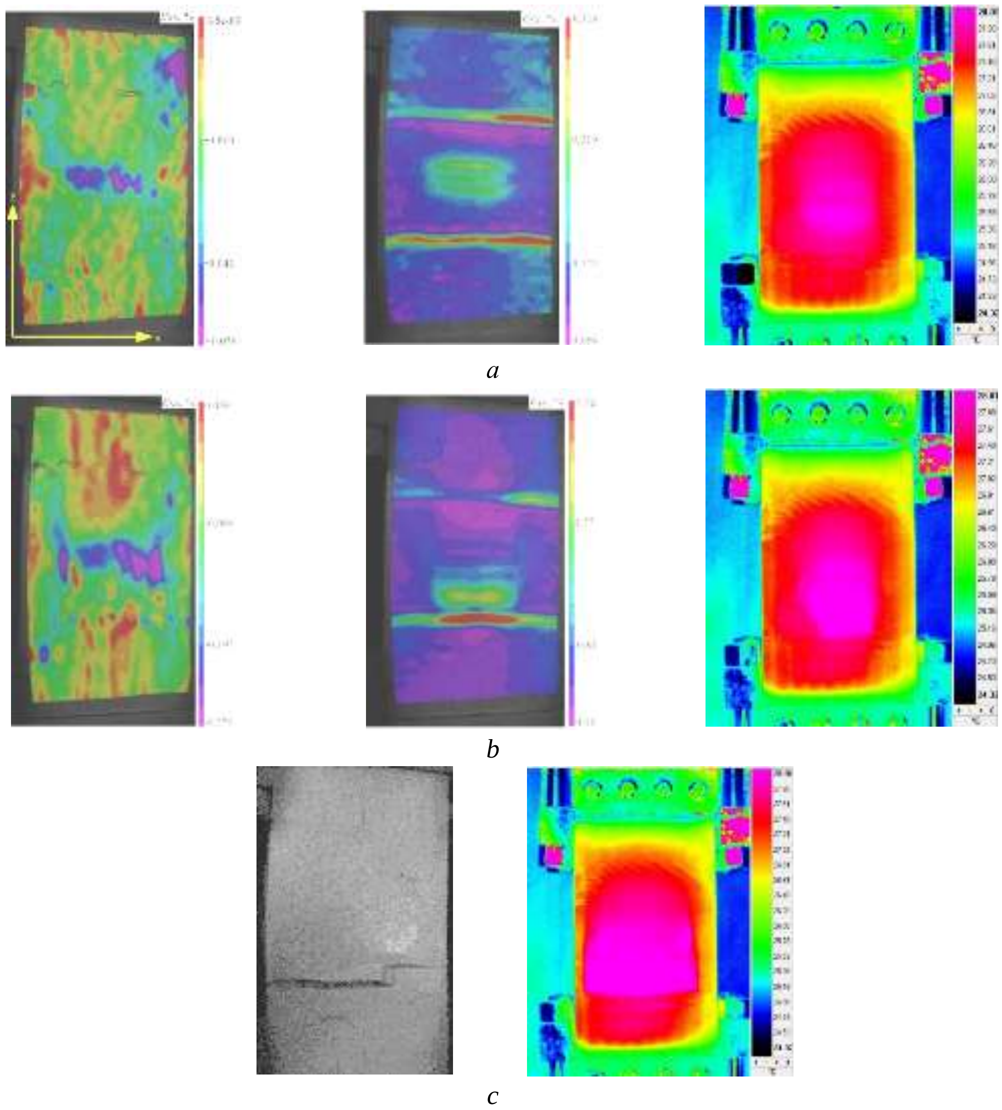
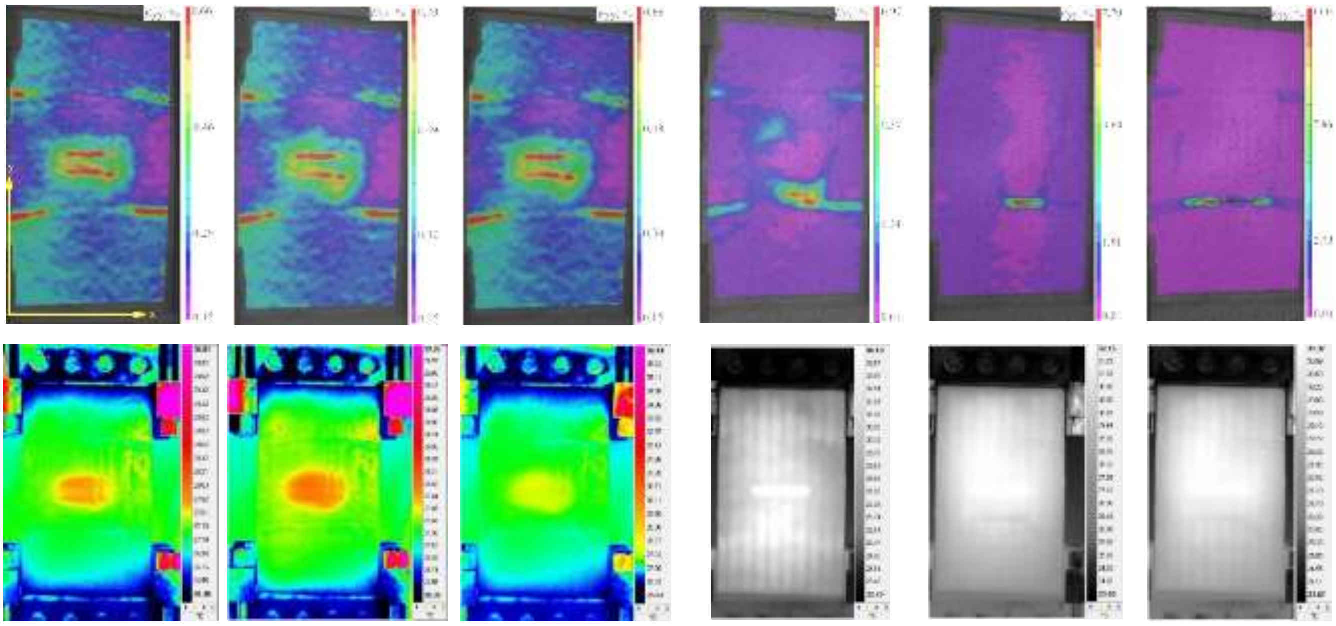


Fig. 4. Deformation fields ε_{xx}, ε_{yy} and thermal images on the specimen's surface during the static tension test (*a*, *b*), the image and the thermogram at the moment of fracture (*c*): *a* – corresponds to point 1 of the diagram; *b* – corresponds to point 2; *c* – corresponds to point 3



n = 50 *n* = 80 *n* = 100 *n* = 160 *n* = 180 *n* = 200

Fig. 5. The evolution of the longitudinal deformations (at the top) and corresponding thermal images (at the bottom), depending on the number of the implemented loading cycles

Also there was a loss of integrity of the contrast finely dispersed coating, which made it impossible to build the deformation fields. Fig. 4 c shows the specimen's image at the moment corresponding to the maximum load of 78 kN at the diagram (Fig. 3, point 3). Then there was a dynamic rupture of the specimen until its ultimate failure. The strength capability decrease of the ASP specimen's with the defect repair zone, compared to the ASP specimen without defects [2] was approximately 20 %.

The cyclic tests were carried out in compliance with the testing program described earlier. It is worth mentioning that at the first stage (first 100 cycles), the development of concentrators of deformations in these zones was not observed. The distributions of the fields of longitudinal deformations and temperatures had a similar shapes, when passing through the inspection points of registration. The deformation fields and thermal images corresponding to 50th, 80th and 100th loading cycles are given in Fig. 5 ($n = 50$, $n = 80$, $n = 100$).

A similar situation was observed at the second stage (another 100 cycles) up to 160th cycle. Later the cyclic loadings were accompanied with a characteristic sound of a crash, after it the further inspection points registered a crack at the centre of the specimen along the repair zone, which was also seen at the distributions of the fields of longitudinal deformations and thermal images, Fig. 5, when $n = 180$ and $n = 200$. Accoding to the registration results of 20 inspection points of the cyclic tests, the diagrams were built regarding the longitudinal deformations' distribution across the width of the tested specimen along the delamination of the lower part of the repair zone, which was located 40 mm lower, than the geometric center of the specimen (Fig. 6). Fig. 6 shows the curves corresponding to the deformations fields (Fig. 5), along which it is also possible to judge at which stage of the cyclic tests, in consequence of the destruction of the adhesive layer and the subsequent delamination, a crack appeared along the edge of the repair zone.

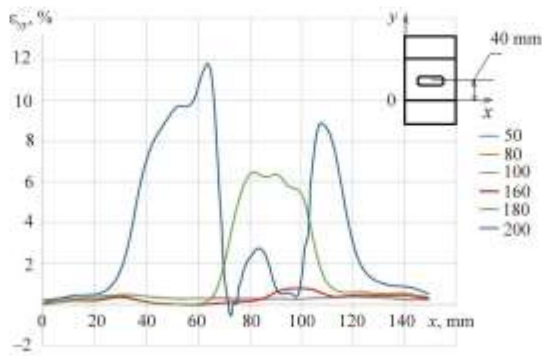


Fig. 6. Diagrams of the longitudinal strain distribution ε_{yy} along the line of the bottom repair zone across the whole width of the ASP specimen under cyclic tests, corresponding to the inspection points of registration, when reaching 50th, 80th, 100th, 160th, 180th and 200th loading cycles

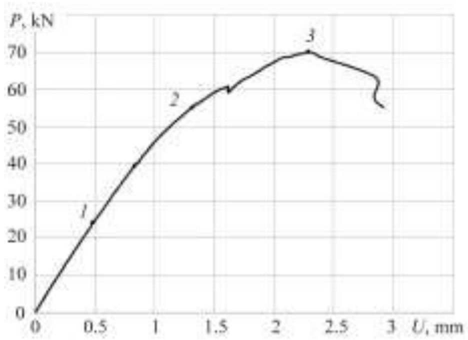


Fig. 7. The loading diagram of the ASP specimen under tensile test after preliminary cyclic effects

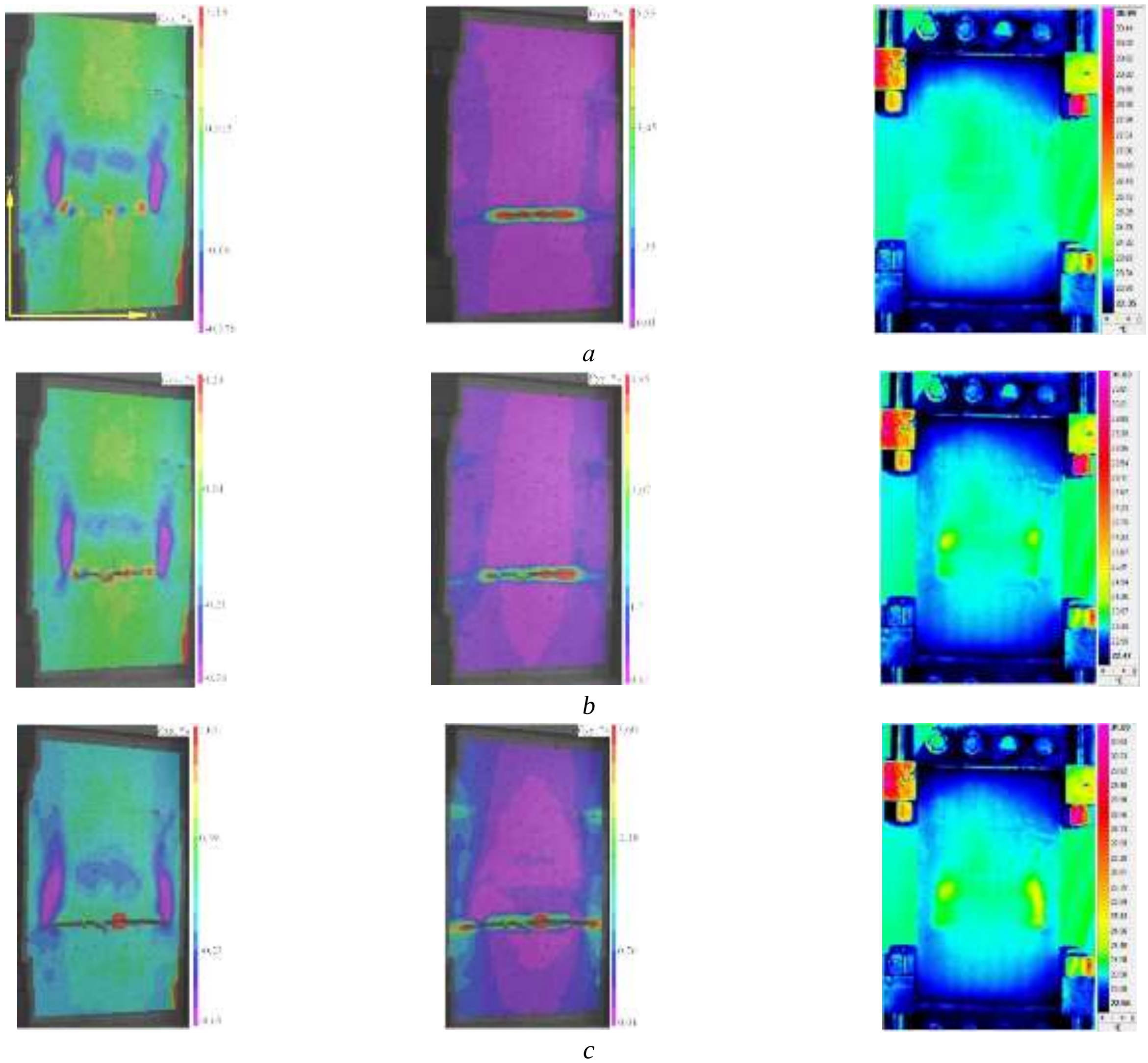


Fig. 8. Deformation fields ε_{xx}, ε_{yy} and thermal images on the specimen's surface in the course of tension under static load testing after preliminary cyclic loadings: *a* – corresponds to point 1 of the diagram; *b* – corresponds to the point 2; *c* – corresponds to point 3

After preliminary cyclic effects, the ASP specimen had tension under static load testing. The loading diagram was built in a similar way, accoding to the data of the video system (Fig. 7).

In the course of loading of the ASP specimen, it was possible to see how the crack was developing, i.e. the delaminations along the edge of the repair zone. Fig. 8 shows the fields of transverse and longitudinal deformations and temperatures, corresponding to the loading points registered at the diagram. By analyzing the sections 1-2 and 2-3 at the diagram, it is possible to make conclusion about a gradual growth of the crack. Point 3 corresponds to the maximum load of 70 kN, after it there was a dynamic break.

It is shown that the load-bearing strength of the specimen with the applied defect is 30 % less, than that of the specimen with a defect [2]. The cyclic loadings accroding to the given modes resulted in the additional decrease of the load-bearing strength by 10 %.

Conclusions

The proposed method of studying the influence of defects on the residual strength of structural elements made from composites by a joint use of the the system registering deformation fields and temperatures makes it possible to get data about the development of external and internal defects. In particular, it can be used to evaluate the efficiency of maintenance and repairs, as well as to select optimal contents of the adhesive layer.

According to the testing results, an additional decrease of the load-bearing strength of the ASP panels after preliminary cyclic effects was established. Hence, for an effective evaluation of the maintenance and repair works for structures made from composites, it is reasonable to take into account not only the results of tension under static load testing, but also the preliminary cyclic effects in the working ranges of loading.

It is worth mentioning that it is necessary to conduct additional testings to evaluate the preliminary cyclic effects, statistical variability, as well as the size of the permissible defect, and, the area of the repair zone.

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