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Strength Tests of 3D Warp-Knitted Composites with the Use of the Thermovision Technique

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Abstract
The article presents the results of strength tests of thin-walled composite beams carried out with the use of the thermovision technique. During a beam bending test performed in a four-point support system using a testing machine, an increase in the value of the temperature on the surface of the beam was observed along with an increase in the bending input function (deflection of the beam). The curve of force (stress) is correlated with curves of changes in the values of heat emitted during the bending process. The maximum value of temperature rise of the bending composite reaches the value of ΔT = 20.02 °C. The process of the bending of a beam is accompanied by a conversion of mechanical energy into free surface energy, thermal energy as a result of damaged atomic and intermolecular bonds, and also thermal energy occurring due to friction force acting between the destroyed surfaces. The experiments carried out confirm the thesis that analysis of the temperature distribution of composites in strength tests is the basis for the quality evaluation of stress distribution in the composites tested.

Key words: *transnational corporations, corporation culture, management.*

Introduction and the aim of research

The polarising and optical method, based on the birefringence phenomenon [1 - 3], is the most commonly used in mechanics and in empirical tests on the stress distribution in structural elements. In this method a flat, transparent model of the object tested is placed in a polariscope, and then a ray of polarised light is transmitted through this object. As a result, we obtain an image of isoclinic and isochromatic lines related to the state and distribution of stresses. Photoelasticity is mainly used to analyse stresses in elements of irregular shape, to detect critical stress points in glass objects and also to analyse polymer structure. Methods based on such measurements include the reflected light method, the transmitted light method and the stress freezing method. The main disadvantage of this group of methods is that there is no possibility to perform tests on real objects. Therefore, it is necessary to produce models from materials of photoelastic properties or to apply special coats reflecting light from the surface of the samples tested, as well as to use a specialised, complex measuring apparatus. Another technique which also requires the use of a special experimental model made of transparent material is the moire technique, using the moire effect, created as a result of overexposing two overlying nets of lines, in which one is distorted, whereas the second one is the model net. Other significant fields that perform stress analyses include strain gauge measurements using strain gauges fixed on the surface of the elements tested, and the brittle coating method, in which the elements tested are covered with a special lacquer that cracks due to deformations, and the crack lines overlap with one of the directions of principal stresses. However, the methods mentioned above have several disadvantages as they directly interfere with the objects tested.

The thermovision technique is a new method which has not been used as yet in strength tests on 3D textile composites. As a signal it uses thermal radiation emitted from the surface of the element tested, subjected to kinematic forcing [4]. The main advantage of this method is that the measurement is performed on real objects, with their size scale remaining unchanged. The basis of thermovision tests is the phenomenon of the conversion of mechanical energy, connected with the process of the deformation of the 3D textile composite, occurring as a result of the deformation of fibre glass material and epoxy resin. Energy conversion occurs as a result of the deformations of the bonds between atoms and macromolecules and because of changes in valence angles in the molecules of composite materials, bringing the system out of the equilibrium state of minimum energy; therefore the entropy of the system decreases the emission of heat. Such an increase in temperature is observed in elastic and viscoelastic deformations. Further deformation of the element causes damage to atomic and intermolecular bonds, leading to permanent, non-reversible cracking of the material. The thermovision technique is a passive method, which means that interference in the structure of the element tested is not required, hence it is performed in a closed thermodynamic system; free exchange of energy occurs without the exchanging of mass with the environment [5]. The subject-matter of strength tests concerns the new generation of 3D warp-knitted composites. The aim of this research was to identify the strength properties of 3D warp knitted composites on the basis of an analysis of temperature fields using the thermovison technique.

Characteristics of materials

In this research samples of 3D composite beams were tested [6 - 8]. The beams were produced from a warp-knitted fabric of the DOS type with the tricot stitch reinforced by wefts in both the vertical and horizontal directions (***Figure 1***). Glass yarn of linear density 3×68 tex was used as a raw material for the warp-knitted fabric, characterised by the following parameters: fabric thickness – 0.21 mm, surface mass – 200 g/m^2, breaking force along the vertical threads - within the range of 198.8 – 217.8 daN, while along the horizontal threads - within a range of 200 – 220 daN; the elongation at break for

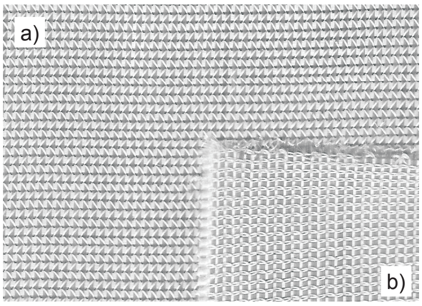

Figure 1. *Photograph of a warp-knitted fabric used for thin-walled composite beams; knitted fabric – inside (a) and outside (b).*

both the vertical and horizontal threads reached the maximum value of 5%.

The knitted fabric was manufactured using an RS 3 EMS warp-knitting machine of needling number 18 E, made by Karl Mayer.

The knitted fabric was hardened to form fibrous composites, for which a hardening agent of the Z-1 type in an epoxide resin of the Epidian® 5 type was used. Samples were formed manually using a mould of rectangular cross-section, with dimensions of 40 × 40 mm. 8 layers of the knitted fabric were wound on the mould mentioned above. For better dripping of glass threads between the layers of the knitted fabric, an epoxide resin previously prepared was delivered, and next each of the layers was pressed to the mould by a rubber roller in order to remove air bubbles and excess of resin.
The winding process was performed along the horizontal wefts of the knitted fabric. The composite beams previously prepared were dried and next cut to the following lengths: 350 mm for bending tests and 200 mm for compressing tests (***Figure 2***).

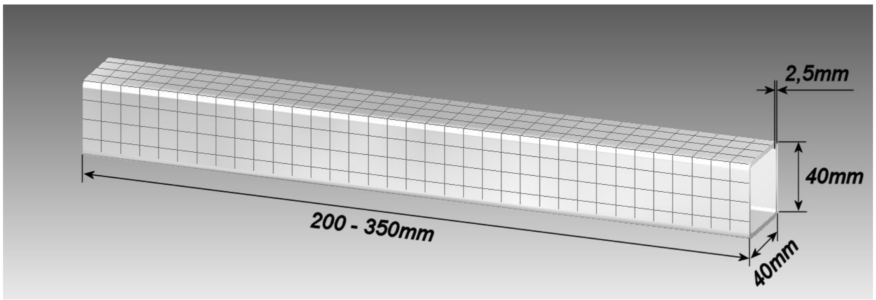

Figure 2. *Model of the composite beam marked with a dimensional net.*

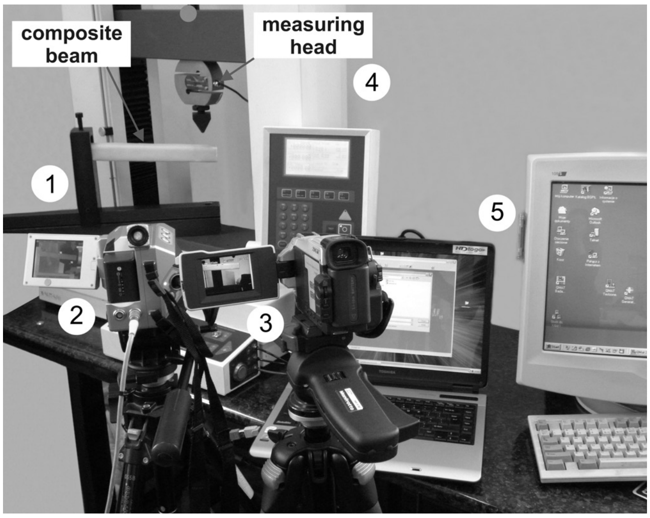

Figure 3. *Stand measuring the strength of composites; 1 - tool chucks for strength test, 2 - thermovision camera, 3 - digital camera, 4 - strength testing machine, 5 - two computer stands.*

Measuring stand and methodology of thermovision testing

For the experiments, a measuring stand (***Figure 3***) was designed including the following: a strength testing machine (Hounsfield H50K-S) equipped with a measuring head of pressure ranging up to 50.0 kN (4), a set of tool chucks for the strength tests (1); a thermovision camera of the VarioCAM® HiRes type, made by JENOPTIK (2); a digital camera of the DCR-TRV-16E type, made by Sony (3); two computer stands (one to operate the strength testing machine, and the other one to record thermovision camera images) (5).

For bending strength tests four different tool chucks were used (***Figure 4***), designed on the basis of Polish Standards PN-EN ISO 14125 and PN-EN ISO 178, and produced at the FAMID factory, Łódź, Poland.

Three of these tool chucks are designed for the analysis of the bending strength properties of 3D composite beams in three-, four- and two-point support systems (***Figure 4.a, 4.b*** & ***4.c***) and in a two-point support system for compression (***Figure 4.d***).

Bending tests were performed with a displacement speed of the measuring head equal to 50 mm/min. In order to analyse the results obtained, the ThermalScope v 2.15 program was used in the measurements with a thermovision camera. The program allows to record and process thermography and thermovision images and also to read temperature values at any point on the thermovision image.

The measurement of temperature values can be performed point wise by selecting an arbitrary point in the picture, along a line by determining a straight line between two arbitrary points, or in a specif-

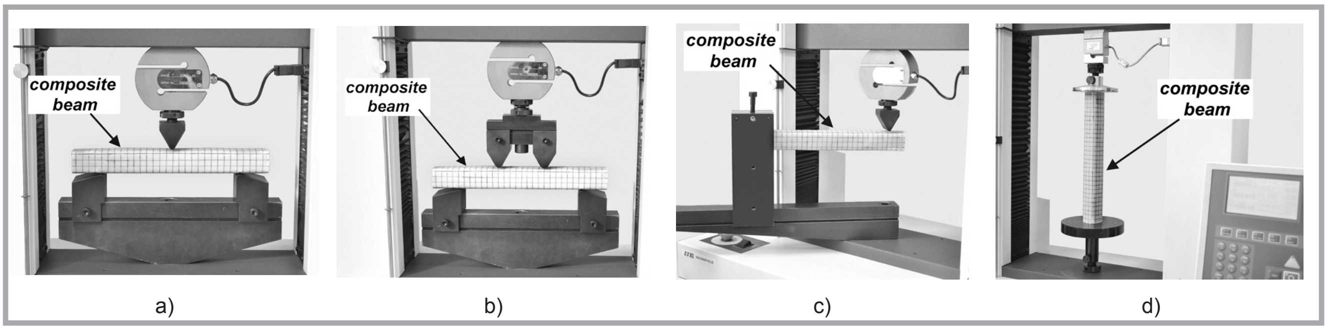

Figure 4. *Tool chucks for composite strength tests: a) for bending in a three-point support system, b) for bending in a four-point support system, c) for bending in a two-point support system, d) for pressing in a two-point support system.*

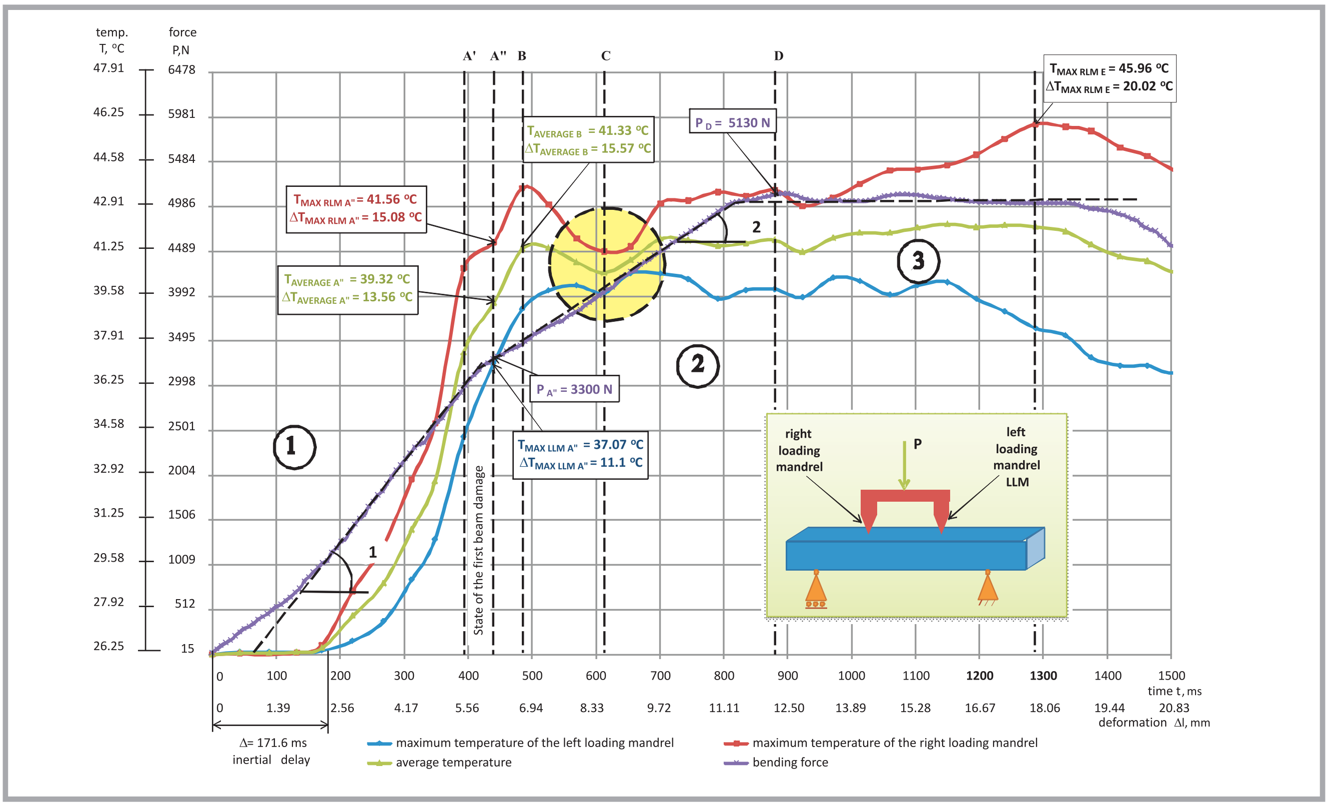

***Figure 5.** Correlation between the forcing of the beam deflection and the temperature of the bending area in the function of deformation.*

ic area by determining its range using elliptical, rectangular or polygonal figures. The emissivity of the thin-walled beams tested was determined using a thermovision camera, equalling $\varepsilon_\lambda = 0.95$, which indicates that the composite material tested is a good emitter of infrared radiation. The measurements were conducted at an ambient temperature of 23 °C and humidity of air of 55%.

Results and analysis

Strength tests were performed for four different support systems of the beam. The variant for bending a composite in a four-point support system was found to be the most interesting and thus submitted to precise analysis. The average initial temperature for this variant was 25.8 °C. It should be noted that the transformations occurring within the area of composite deformation as a result of kinematic forcing are a very complex physical phenomenon. Moreover an important fact is that before the strength test the beam is placed in a stationary sourceless vector field of temperature; however, due to forcing, the field is transformed into a non-stationary source field, in which heat exchange takes place as a result of radiation, conduction and convection.

In this research only one of the two symmetrical sides of the beam were observed using thermovision and digital cameras. The analysis presented is simplified, not taking into consideration the structural character of the beam. For better analysis, distributions of the temperature should be identified in all four walls of the composite: two vertical and two horizontal. It can be assumed that the vertical and horizontal surfaces of the bending beam will have different characters of temperature distributions correlated with the stress distribution. What is more, the upper horizontal surface of the beam is subjected to the process of compression, while the lower surface - to the process of stretching, with different solutions of support systems, which results in different stress distributions (temperature distributions). Furthermore one should keep in mind that walls of the beam's cuboid of defined thickness will have different characters of stress in the external and internal layers of the composite.

Figure 5 presents a correlation of the forcing of beam bending and the temperature of the bending area as a function of the beam deformation. The violet curve describes the character of changes in the values of the bending force in time; the red and blue curves describe the changes in values of the maximal temperature for the right and left loading mandrel, respectively, while the green curve outlines the changes in values of the average temperature for both of the loading mandrels. The area between points A' and A", on the graph marked in red, presents the state of the initial damage of the beam in the form of micro cracks. A further

***Table 1.** Values of temperature T, temperature gains ΔT and forces P for characteristic points A' to E.*

Point	$T_{MAX\ RLM}$, °C	$\Delta T_{MAX\ RLM}$, °C	$T_{MAX\ LLM}$, °C	$\Delta T_{MAX\ LLM}$, °C	$T_{AVERAGE}$, °C	$\Delta T_{AVERAGE}$, °C	P, N
A'	40.60	14.84	34.35	8.59	37.48	11.72	3000
A"	41.56	15.08	37.07	11.31	39.32	13.56	3300
B	43.58	17.82	39.08	13.32	41.33	15.57	3450
C	41.23	15.47	39.69	13.93	40.46	14.70	4043
D	43.51	17.75	39.83	14.07	41.67	15.91	5130
E	45.96	20.02	38.38	12.62	42.17	16.41	5040

increase in bending results in a consecutive deformation of the beam. A decrease in temperature in the bending composite, on the graph marked in yellow, is characteristic for a visible cracking of the beam in the full height of its wall. The values of temperature T, gains in temperature ΔT and force P for characteristic points A'-E, presented in ***Figure 5***, are given in ***Table 1***. Significant differences in the values of temperature for the left and right loading mandrel, observed in the graph, can result from an inaccurate levelling of the upper part of a tool chuck. In the analysis of the bending process of a thin-walled composite beam performed in a four-point support system, an inertial delay $\tau = 171.6$ ms can be observed, which refers to an increase in the values of temperature, responding to the forcing signal constant in time, being a kinematic displacement of the measuring head. The displacement is the response (work) of the bending composite beam. In the analysis it was observed that in particular areas, the curve of force gain changes its character of the course. In the following graph there are three areas presented - 1, 2 and 3, in which the angle of the curve slope P(t) changes.

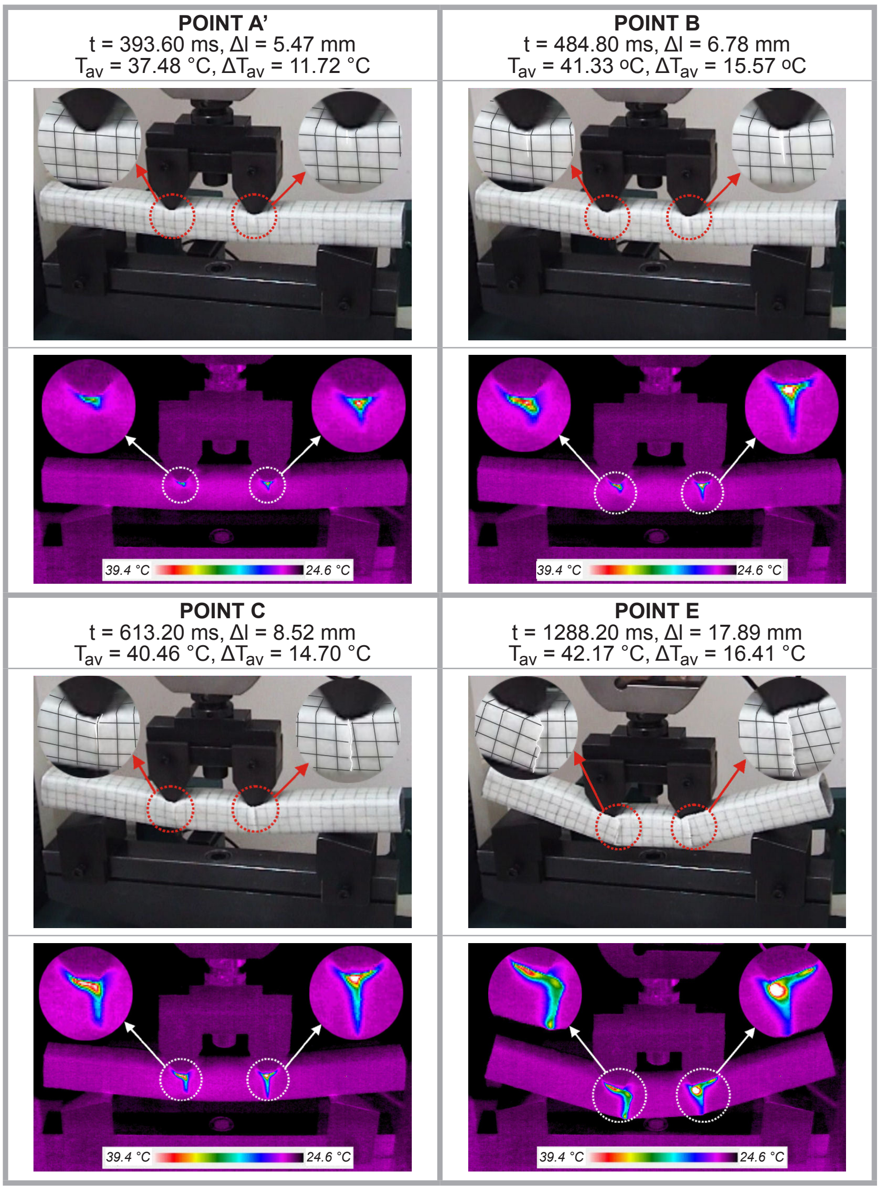

Figure 6. *Digital photographs and thermograms of characteristic points (A', B, C, E) of the composite beam strength tests in a four-point bending system.*

Area „1" is within the range of the bending of the beam, treating it as a visco-elastic object with reversible deformations. A high gain in force, reaching a value of 3 kN, is observed in this area. Within the range of these deformations, a significant increase in temperature, reaching a value of 39.3 °C (ΔT = 13.56 °C), was also observed due to atoms unbalanced from the equilibrium state, characterised by minimal energy and the formation of micro cracks in the structure of the composite, which resulted from heat emission. A conversion of mechanical energy, Em, into free surface energy, Es, of the new surfaces created (micro cracks formation) and heat energy Ec takes place. In area "2", in which significant damage to the element tested and, thus, permanent deformations occur, a change in the run of the curve of force gain can be observed. The angle of its slope, α_2, decreased in relation to angle α_1, and consequently the value of the rigidity coefficient changed as well. A decrease in the value of heat emitted was a result of the consecutive breaking of the main chemical bonds in macromolecules. The cohesion of the object was damaged due to external forces, leading to permanent non-reversible damage to the beam, which explains the decrease in the values of temperature. In area "3" a further increase in temperature was observed for the right loading mandrel, despite any increase in the value of the force. Heat was emitted as a result of the further deformation of hitherto undamaged atomic and intermolecular bonds, and as a result of friction when the composite layers came in contact. In this area the mechanical energy, E_m, delivered was converted into a sum of three constituent energies: free surface energy E_s, heat energy as a result of damaged atomic and intermolecular bonds E_{cw} and heat energy E_{ct} as a result of friction force, which can be described as the following dependence: $E_m = E_s + E_{cw} + E_{ct}$.

Both images of the bending beam and thermograms were registered at a suitable frequency: 25 frames/s for the digital camera and 1.15 frames/s for the thermovision camera. The graph presents six characteristic points describing the behaviour of the composite strength process.

Four of the bending points of the 3D thin-walled composite beam selected are presented in ***Figure 6*** as photographs of real deformations and corresponding thermovision images. Additionally, the images present enlarged areas of deformations and damage of the composite. Point A' illustrates the moment of the first damage to the beam tested, in which the bending force reached a value of 3.0 kN and the maximum temperature increased in relation to the initial temperature of the beam, reaching 34.3 °C (ΔT = 8.59 °C) for the left loading mandrel and 40.6 °C

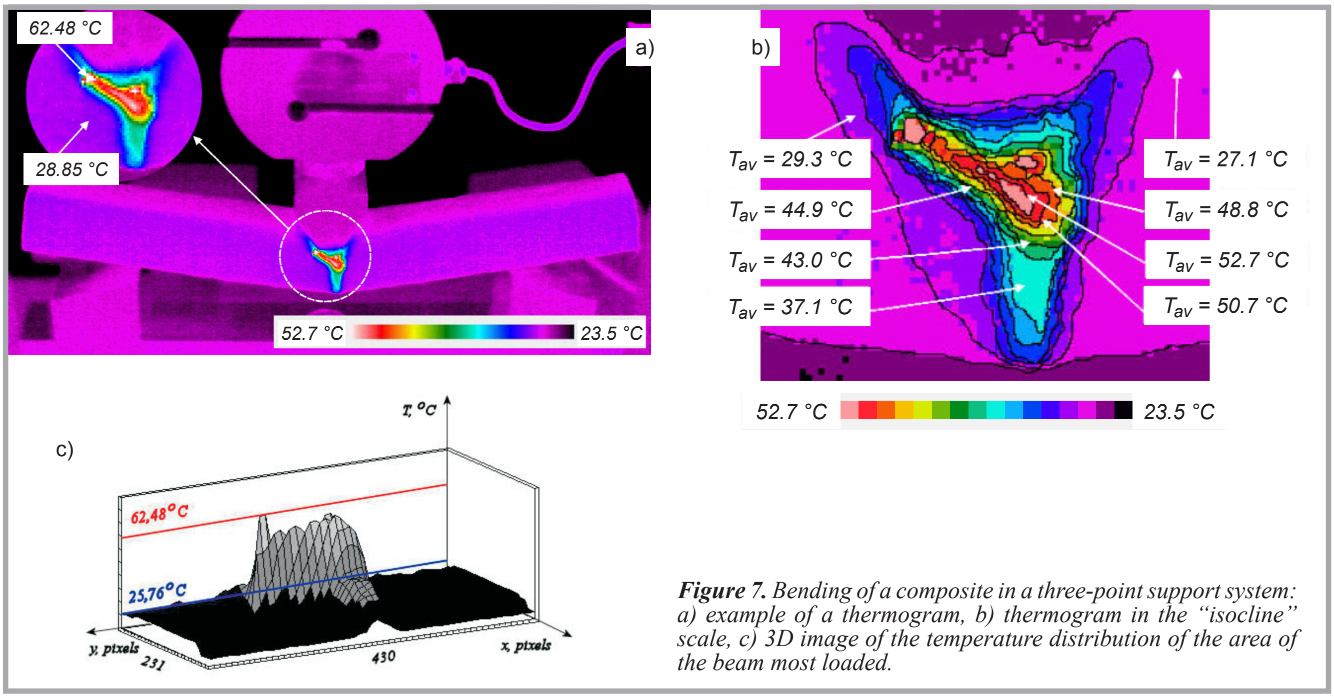

Figure 7. *Bending of a composite in a three-point support system: a) example of a thermogram, b) thermogram in the "isocline" scale, c) 3D image of the temperature distribution of the area of the beam most loaded.*

(ΔT = 14.84 °C) for the right loading mandrel. Point B illustrates a distinct crack in the composite of 20 mm depth. The bending force reached a value of 3.450 kN, while the maximum temperature was 39.1 °C (ΔT = 13.32 °C) for the left loading mandrel and 43.6 °C (ΔT = 17.82 °C) for the right loading mandrel.

At point C the crack of the composite deepened, reaching almost the full length of the side wall of the composite. The bending force at this point reached a value of 4.043 kN, while the maximum temperature for the left loading mandrel was 39.7 °C (ΔT = 13.93 °C) and for the right loading mandrel – 41.2 °C (ΔT = 15.47 °C). Point E illustrates visible damage to the side wall of the composite, in which the elements of the beam tested overlay each other. The bending force at this point reached a value of 5.040 kN, and the maximum temperature observed here was the highest, reaching 46.0 °C (ΔT = 20.02 °C) for the right loading mandrel, while for the left loading mandrel the temperature slightly decreased, reaching 38.4 °C (ΔT = 12.62 °C).

Figure 7.a presents an example of a thermogram in a three-point bending system for a thin-walled composite beam. Boundary values of the temperature in the area of destruction of the beam are presented enlarged. ***Figure 7.b*** presents a thermogram made on the basis of a special selection of scale, in which the areas of temperature form lines known as isotherms. A thermogram was made for the area of deformation, presented in ***Figure 7.a***. The isotherms obtained correspond with the isochromatics of principal stresses, obtained with the use of the elastooptic method for beams of similar shapes, which are geometric loci of points with a constant value of the maximum load of the beam [1, 3]. The range of scale enabled to divide the area into 16 subareas of diversified temperature, changing at every 1.95 °C.

The distribution of strength stresses of thin-walled composite beams can be evaluated using an analysis of temperature areas of these objects. Taking into account the changes in elastic and viscoelastic deformations, it is possible to determine a functional correlating the character of the gains in temperature values depending on the values of stresses. For the variant of composite bending mentioned above, a 3D image of the temperature distribution of an area of the beam loaded the most was made in order to present clearly the changes in the distribution of heat emitted (***Figure 7.c***).

The process of the two-point vertical compression of thin-walled composite beams is interesting, yet some commentary is necessary. The beams used in the compression process had the same geometrical dimensions as those used in the bending process; only their length decreased to 200 mm. A surprising effect of the damage process performed were the different reactions to the pressing force. In the first case (***Figure 8.a***) damage was observed in the upper part of the beam consecutively with the forcing added. In the case of the beam presented in ***Figure 8.b***, the destruction was of a totally different character: a sort of cutting of the side layers of the test object took place. The maximum increase in temperature observed for both samples was around the same value - in the range of 57.7 ÷ 61.7 °C, thus the gain in temperature comparing to the initial value of the temperature of the beam tested was within the range of ΔT = 30.99 ÷ 35.28 °C. The character of the different deformation processes of the composite beams could be caused by material defects resulting from the unevenness of the composite structure, that is the resin as well as textile reinforcement in the walls of the beam.

The research presented confirms the thesis that it is possible to determine in terms of quality, and maybe also in terms of quantity, the distributions of stresses in strength tests of composites using an analysis of areas of differentiated gains in temperature on the basis of the thermovision technique. In the case of the quantity evaluation of the stress distribution, an analysis of the heat balance of beam bending should be performed taking into account the law of conversion and conservation of energy from the point of view of thermodynamics.

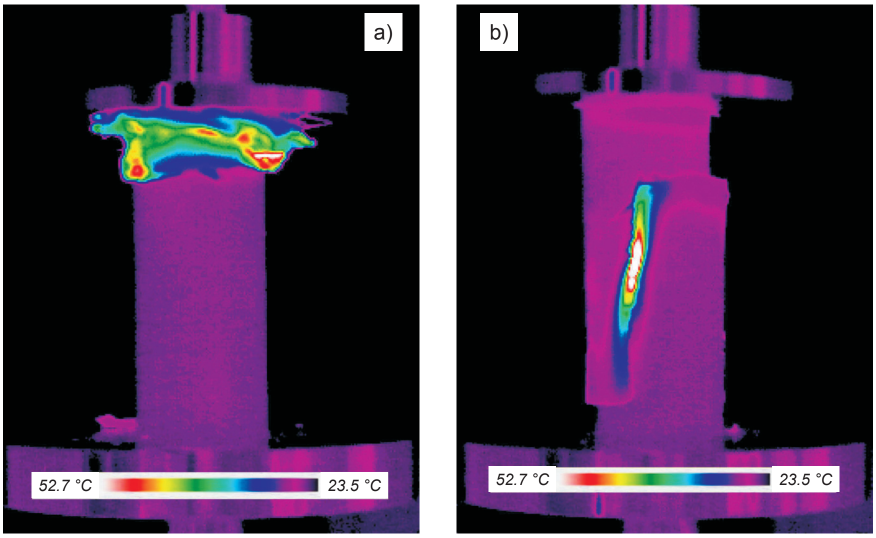

Figure 8. *Exemplary thermograms of compressing a thin-walled composite beam with different effects of its destruction.*

The empirical tests on fibrous composite materials presented in this article, as well as research tests carried out in Poland and abroad, analysing the phenomenon mentioned above, which occurs in steel and concrete objects [9 - 11], are confirmation of the thesis assumed. It is noted in the literature that heat emission occurs along with the formation of stresses in structural elements. The shapes of the area of temperature distribution observed in the thermograms obtained correlate with their geometry to the area of stresses presented in scientific publications.

The authors of the publications analysed state that particular values of stresses in the elements tested are correlated with adequate values of temperature, according to the following dependence: $б = k \cdot T$, where: б – stress, T – temperature, k – correlation coefficient. However, this dependence refers only to tests of elastic deformations. In the case of elastic/plastic or plastic deformations, it is much more complicated, but it does not mean that they cannot be described by mathematical functions of temperature and stress dependencies.

Summary

- The research tests presented enable to conclude that the thermovision technique used in the strength tests on 3D thin-walled composites is a non-invasive method, which is based on the measurement of heat radiation emitted from the surface of a real structural element tested.

- In the analysis of results for a bending 3D thin-walled composite beam in a four-point support system, it was observed that the different slope of the stress and temperature curves, changing in particular zones, occurred at a constant deflection rate. The curve of force (stress) is correlated with those of changes in heat radiation emitted (temperature difference) during the process of bending. Their character is closely connected with the changes in kinematic forcing. In the first area a rapid increase in temperature was observed, reaching an average value of 39.3 °C (ΔT = 13.56 °C). At the time of the first crack the value of the destructive force was 3.3 kN. In the second area a rapid decrease in the heat emitted occurred due to the loss of the cohesion of the composite material and damage to the beam. A phenomenon accompanying the effect of external forces acting on the structural composite element can be explained by the thermodynamic theory of composite strength, according to the first law of thermodynamics.

- The experimental tests performed confirm the thesis assuming that an analysis of the temperature distribution of composites in strength tests enables to evaluate in terms of quality, and in the future also quantity stress distributions in tests on composite materials. The results presented in this article are an introduction to a deeper analysis of phenomena occurring in the strength processes of composites, describing the correlation between the temperature distribution and forcing, as well as stresses in these composites.

Editorial Note

Tests using thermovision method were performed thanks to the cooperation of Prof. B. Więcek with the Institute of Electronics of the Technical University of Łódź.

Acknowledgment

This work was (partially) supported by structural funds of the frame of the project titled 'Development of research infrastructure of innovative techniques and technologies of textile clothing industry' CLO – 2IN – TEX, financed by Operational Programme Innovative Economy, 2007-2013, Action 2.1.

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Received 29.11.2010 Reviewed 04.07.2011