Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 59
ISSUE 1
July
2013

Simulation diagnostics of the polyester-glass pipes degradation process; experimental basis

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Received 21.04.2013; published in revised form 01.07.2013

Analysis and modelling

ABSTRACT

Purpose: In the work is described the method that enables identification of controller of simulation procedures which ensures compliance of experimental research results of changes in material physical characteristics with the characteristics of the numerical model.

Design/methodology/approach: The work presents the method of diagnostic assessment of residual strength of composite pipes produced with the use of the method of winding glass fibre impregnated by chemically setting polyester resin, subjected to fatigue load in condition of pulsating fluid pressure.

Findings: The basis of assessment is the correlation of residual strength with the acoustic characteristics of composite coating of the researched pipes.

Research limitations/implications: The parameters of simulation procedures which are of key importance for correctness of diagnosis were determined on the basis of results of non-destructive and destructive testing of pipe material samples, subjected to the load in conditions corresponding the working ones.

Practical implications: The diagnostic tool is the simulation program of degradation process of composite material with set structure, which enables investigating the changes in material characteristics for any operating load program.

Originality/value: The paper presents a new approach to diagnostic processes of destruction aging-fatigue for the purpose of assessing the residual strength of composite pipes using computer simulation methods.

Keywords: Engineering polymers; Mechanical properties; Non-destructive testing methods; Simulation diagnostics

Reference to this paper should be given in the following way:
M. Szymiczek, G. Wróbel, M. Rojek, T. Czapla, Simulation diagnostics of the polyester-glass pipes degradation process; experimental basis, Journal of Achievements in Materials and Manufacturing Engineering 59/1 (2013) 37-47.

1. Introduction

The technical progress in the field of materials engineering with reference to its application in the area of machine building, pipeline, car and aircraft industry, to mention a few, outlines a firm direction of development which is based on replacing traditional metal materials with polymer composites. These materials provide a valuable possibility of individual design of properties for not only structurally homogeneous products, such as, rods, profiles, plates or coatings, but also individual shaping of properties of chosen construction elements with their whole complexity of geometrical shapes and utility functions. Additionally, it is possible to take into account the strength requirements as well as thermal, electrical and esthetical characteristics. The cost of production and the drawn cost of exploitation is competitive in case of mass production, which motivates to more intensive search for new solutions, particularly in the period of economic crisis and intense competition. The barrier is the bigger characteristics spread which, first of all, results from technological possibilities of ensuring repeatability of geometric and structural features of the material. Another cause might be the influence of environmental conditions of exploitation, and eventually long-lasting fatigue and ageing processes, which constitute the factors that should be taken into consideration at the stage of construction design and forecasting the conditions of its safe exploitation.

Solutions to the issue of repeatability of material geometric and structural features is looked for by means of technological improvement: replacing the method of open moulding with the ones supported by vacuum technology (infusion), RTM, press moulding. Utilizing pressure in the forming stage also enables increasing the content of reinforcing fibres as well as the elimination of voids and discontinuities which reduce the quality of the product. Obtaining repeatable output characteristics of the product constitutes the important premise of quality. In arrangements, in which particularly important are strength properties of elements that determine their reliability and the safety of use, the current monitoring of the state of degradation - exhaustion of load-bearing capacities, plays a crucial role [33,34]. In the changeable exploitation conditions or the lack of thorough knowledge concerning their case story, only the present condition of the material might serve as a source of information and make the basis of assessment of effectiveness and safety of further work. In order to produce such assessment, diagnostic methods are applied.

The program of research concerning tubular elements described in the further points, makes a good example of the utility of diagnostic methods and usefulness of their application in conditions of periodic inspection of flow networks.

Drawn up methodology of diagnostic procedure is based on the results of basic research within the scope of application of non-destructive techniques: ultrasonic and thermovision, for the assessment of changes in strength properties of polymer composites. [3-8, 10-19, 21,22,24,28]. The assessment of the condition of a composite element, results from diagnostic relation of acoustic and thermal characteristics of the material as well as its residual strength that can be determined in a non-destructive way. Thus, its utility tool may be an ultrasound head or a thermovision camera, which enable the intermediate investigation of the material condition.

Irrespective of the possibility of conducting the research of the exploited systems, the issue of operational durability of composites is of great importance since the designing stage, when even estimated assessment make a valuable premise while selecting geometric and material construction properties of elements. At this stage the tool supporting designer's work might be the virtual diagnostic simulation [9,20,25,26] meant as numerical analysis of the element degradation process. The outlined simulation procedure requires the identification of the drivers determining the evolution of the computational model proceeding in accordance with experimental observations, conducted on the material (composite) with similar structure in the conditions of exposure to similar degradation factors (ageing, fatigue).

In point 2 we discuss the methodology of experimental research, the pipe elements and the samples of selected composite material were subjected to. Within point 3 we describe the numerical model of composite, the manner of its physical parameters identification and the procedure of simulation research of fatigue and ageing processes which enables the assessment of the degree of loss of pipes load-bearing properties–residual strength of elements.

2. Experimental research on composite pipe elements

The research is conducted in a multiple-way manner. Their program embraces:

- ageing-fatigue load of pipe samples of composite material,
- non-destructive determining of material acoustic characteristics in conditions corresponding to the selected numbers of load cycles,
- non-destructive determining of thermal material characteristics in conditions corresponding to the selected numbers of load cycles with thermovision method,
- determining the strength characteristics of material samples in conditions corresponding to the selected numbers of load cycles,
- determining the thermal characteristics of material samples in the conditions corresponding to selected numbers of load cycles with the application of the contact method

In Table 1 we juxtaposed the numbers of cycles determining the subsequent phases of research, throughout which the control examination are conducted.

Table 1.
Number of research cycles ageing-fatigue

No of research	1	2	3	4	5	6	7	8	9
No of cycles*10^3	2.5	5	10	15	20	30	60	100	150

2.1. Ageing-fatigue research on samples of composite pipe materials

The research is conducted on a workstation shown in Fig. 1. The pipe samples (PR) in the shape shown in Fig. 2a and dimension shown in Fig 2b, mounted in holders in a manner shown in Fig. 3, are subjected to the load which is periodically forced by variable internal pressure, which parameters change are subjected to programming with the use of panel controlling hydraulic circuit forcing system working conditions.

Loading of samples is conducted in conditions of thermostated water bath. The temperature of the bath is inflicted - within the range from the ambient temperature to that close to the boiling point. The study was conducted at 30^{o}C. There can be 5 samples in the bath at the same time. The counter registers the number of loading cycles and enables programmed intervals which in turn allows conducting the non-destructive research in subsequent phases of ageing-fatigue process. These are listed non-destructive research of acoustic characteristics of material with the application of ultrasonic method as well as non-destructive research of thermal characteristics of the material with the use of thermal imaging camera. In case of loss of tightness (perforation of the sample) also the disconnection of load circuit occurs for this sample. The program of the research embraces the destruction of the part of the samples within the test conditions, but also a break of the test in its various phases with reference to samples, which did not lose tightness, but were planned to be cut for samples type NOL (PN) for destructive tensile tests, samples (PG) for destructive bending tests, and for non-destructive thermal tests (PC).

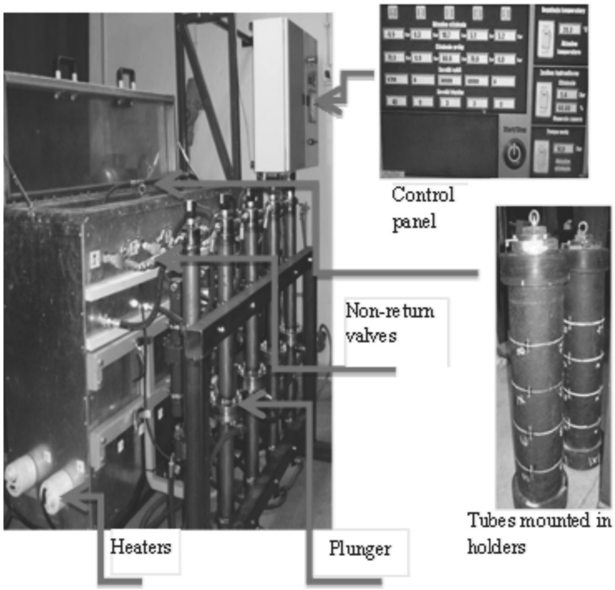


Fig. 1. Working station

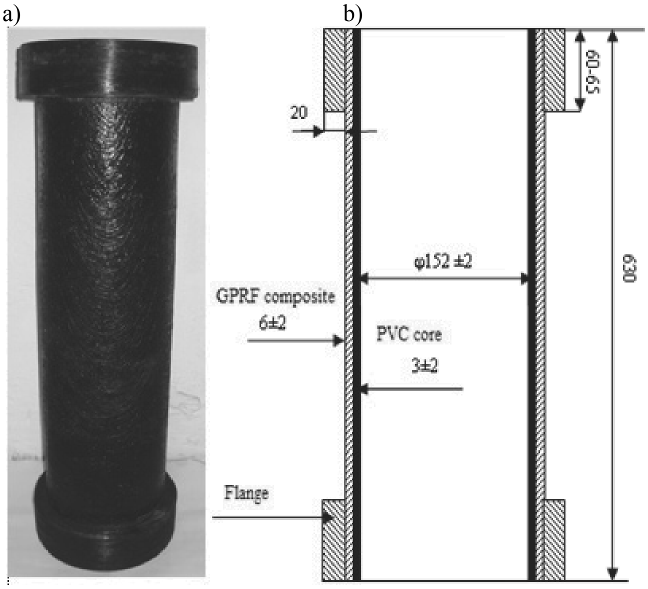


Fig. 2. Sample pipes - a)sight and b) dimension

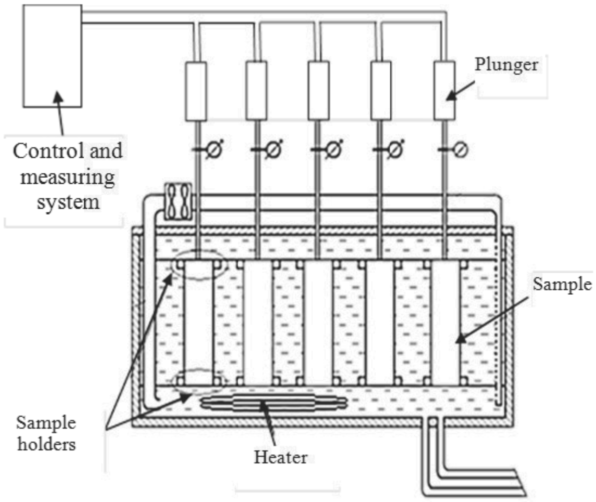


Fig. 3. Scheme of fixing samples in hydraulic circuit.

2.2. Non-destructive testing of material acoustic characteristics with the use of the ultrasonic method

PR are subjected to these research in the separate phases of the degradation process. The basic characteristic determined during the measurement is the transition time of the reflected acoustic signal - time of transition is determined on the basis of the course of the acoustic wave registered with the ultrasonic head in selected points of the external surface of samples. For research, a 2.25 MHz head is applied, the selection condition of which was the quality of the achieved signal for the examined composite. Fig. 4 shows the distribution of measurement points determined by four symmetrically located points creating cylindrical surface and four equidistant planes of transverse sections of pipe samples. Fig. 5 shows the scheme of measuring system and sample course of the measurement signal with marked the transition time t_p.

The measurement of transition time was conducted on the samples both before ageing and taken out of the bath in the moistened state, at ambient temperature.

In the scope of ultrasonic diagnostics of tested materials, the achieved results may constitute, in combination with the results of the destructive tests, the basis for building the diagnostic relationship. [12,13,16,21,22,27].

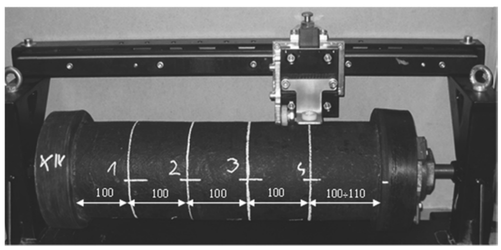


Fig. 4. Distribution of points on the surface PR

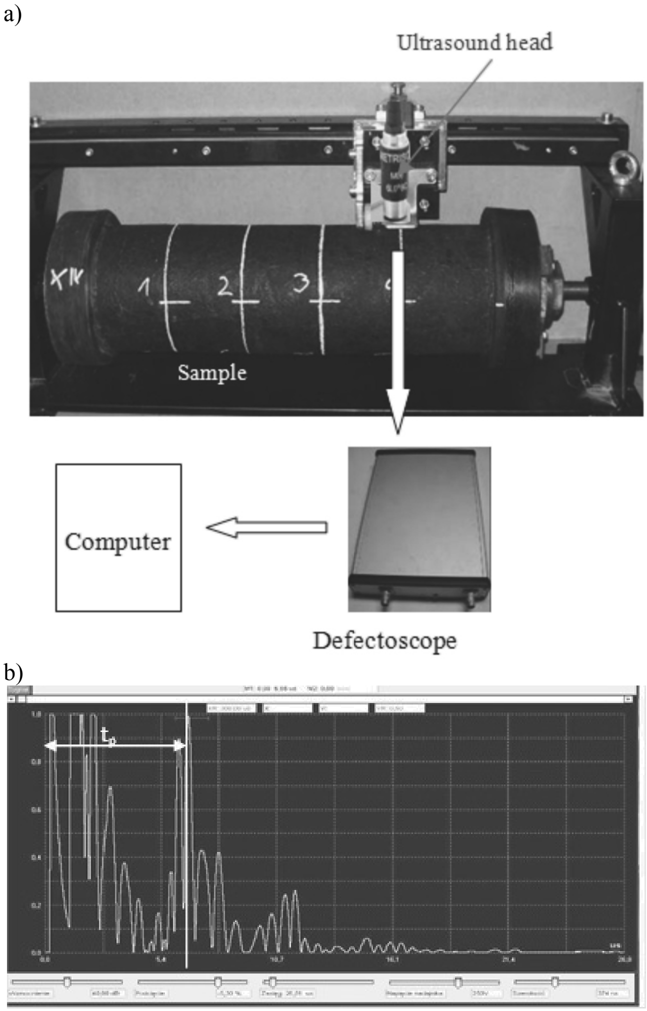


Fig. 5. a) Scheme of the measurement system and b) sample course of measurement signal with marked transition time - t_p

2.3. Non-destructive testing of material thermal characteristics in the state corresponding to given number of load cycles of thermal imaging method

PR in the subsequent phases of degradation process are subjected to these tests, which are conducted as systematically as ultrasonic tests. The basic characteristics determined during the measurements with the use of thermal imaging is the course of PR surface temperature in the vicinity of the same points, in which the ultrasonic measurement is conducted, which is the response to sample short-term irradiation with a halogen lamp. In repeatable conditions (Fig. 6), within the period of 60s, the activated lamp causes the heating of the surface. Induced by forced increase in surface temperature, the process of heat flow in the internal radiation zone could be with good estimation interpreter as the heat flow in the radial direction of the pipe. The process of flow lasts after switching off the lamp. Variable temperature distribution image is subjected to recording in the surrounding of the selected forming PR since the moment the lamp is switched on. The recording of the course of temperature in chosen checkpoints is subjected to particular processing. As characteristic features of this course we accepted the temperature of samples heating after the period of 60s (T_n), cooling temperature after the period of 80s (T_s), and the cooling rate (Fig. 7.).

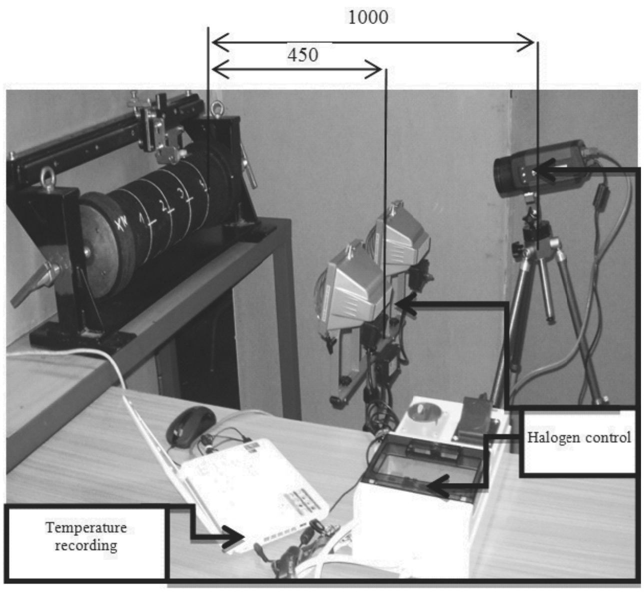


Fig. 6. Diagram of the measurement system of thermal process activated by halogen lamp

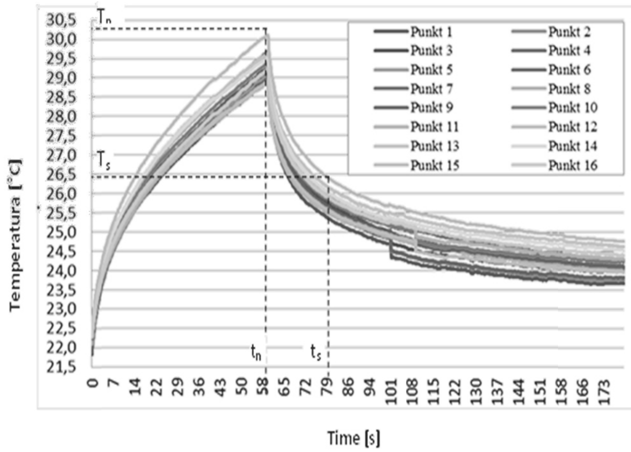


Fig. 7. The example of the temperature course in selected points of PR surface with marked characteristic features (heating temperature - T_n, cooling temperature- T_s, heating time - t_n, cooling time - t_s)

Determining, on the basis of this course, the fundamental features of the material, such as thermal conductivity, specific heat or diffusivity in an exact way is not possible, due to, among others, difficulties with constructing and identification of the physical model taking into account non-determined nature of the process in condition of variable temperature of the surface, the changes in physical parameters as a result of wall PR drying process, complexity of the process including the radiation and cooling phases, impact of the complex boundary conditions. In this case we decided to take the intermediate way of determining these parameters. We undertook the task of constructing the diagnostic relationship of physical parameters - thermal conductivity λ and specific heat c, on the basis of convergence of characteristics of the courses of recorded temperature time in conditions of the process of radiation-cooling T(t) of the pipe with analogical processes recorded on the samples cut out of pipe samples, provided for testing the physical properties with the use of the contact and calorimetric methods (described in the further subsections). Determining the thermal conductivity and specific heat with the use of thermal and calorimetric methods does not cause such difficulties. It is researched in which way the characteristic features of the course of changes in temperature (T_n, T_s, t_n, t_s), in conditions of halogen radiation of the samples, are correlated with the basic thermal features λ (T_n, T_s, t_n, t_s), c (T_n, T_s, t_n, t_s), in order to using this way be able to determine λ and c by non-contact method, with the use of a thermal imagining camera, taking advantage of the courses recorded on pipe samples.

In the scope of thermal imaging diagnostics of the tested materials the achieved results may constitute, combined with the results of destructive testing, the basis for forming the diagnostics relation [7,8,11,19].

2.4. Determining strength characteristics of material samples in the condition corresponding to the selected number of load cycles

The program of research predicts part of pipe samples for cutting into PN samples which enable conducting the destructive strength testing under the tensile conditions.

Establishing strength characteristics of NOL (PN) samples under the tensile conditions

The view of the working station for establishing the characteristics of tensile ring samples is shown in Fig. 8.

Tensile characteristics for PN samples of pipe material are established in various phases of progressive degradation, described by the number of working cycles N of load PR in given conditions (load amplitude A, temperature of bath T), are the basis for establishing the relationship of the tensile strength R_m (N) (residual strength) of composite of the number of cycles N. Fig. 9 shows the demonstration image of the destruction of the sample NOL, originating from the pipe with load history (A=35 MPa, T=30°C, N= 4180), as a result of the tensile test.

Example of regression functions achieved as a result of estimation of parameters on the basis of selected set of measurements of strength are shown in Fig. 10.

a)

b)

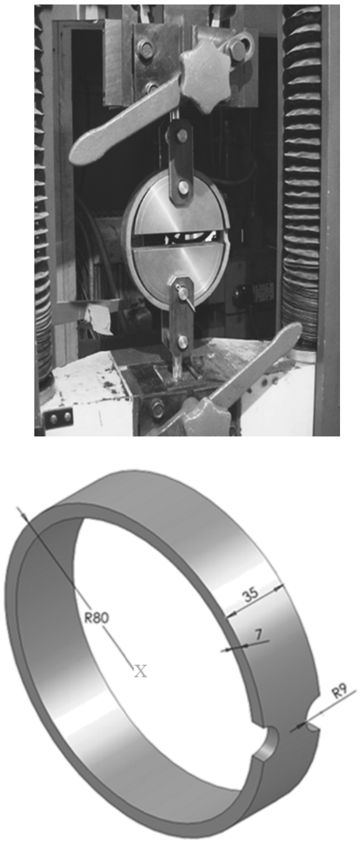
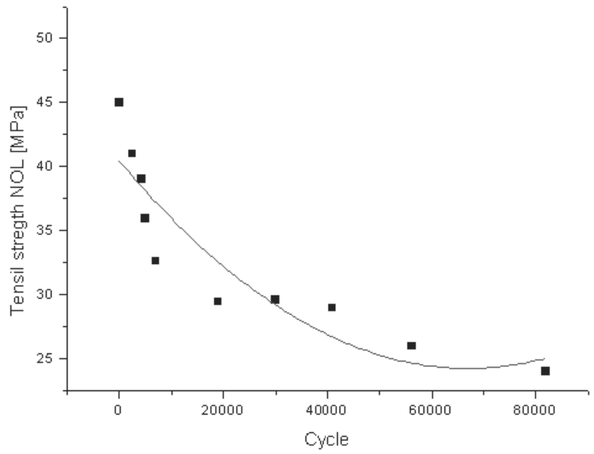


Fig. 8. The view of the working station for establishing tensile characteristics PN (a) and the sample dimension (b)

Fig. 9. Image of sample after tensile test NOL (A=35 MPa, T=30, N= 4180)

Replacing value of Young's modulus depends obviously on fibres and matrix features, the structure of strengthening, and proportion of phases. The process of fatigue-ageing degradation runs in conditions of limited changes in ingredients features (mainly the matrix) with the substantial impact of cumulating material discontinuities. The development of cumulation effect of generated discontinuities runs in conditions of appearing delaminations, adhesive fractures, and fibres fractions. In layered composite structure -45/45, in conditions of average tensile stress in direction 0, in the filled with resin interlayer zones and between parallel arranged roving fibres, there will appear considerable shear stresses. Due to relatively low strength to shearing and endurance to adhesive fractions, the destruction mechanism dominates over the effect of longitudinal tearing of fibres. The results of statistical research PN will be used for identification of parameters of numerical simulation procedure of degradation process which embraces defects generation mechanism in the scope of compliance of model characteristics with those experimentally determined.



Equation		Polynomial	
R value		0.91619	
		Value	Standard Error
NOL	Intercept	40.42329	1.63473
	B1	-4.83294E-4	1.27877E-4
	B2	3.60949E-9	1.62834E-9

Fig. 10. Examples of regression functions of the results of tensile strength measurements $R_m(N)$ for selected set PN

Establishing the strength characteristics of beam tests under bending conditions

The view of the working station for establishing the characteristics of beam samples bending and samples measurements are shown in Fig. 11.

The characteristics of bending of samples PG of pipe material in different phases of progressive degradation described by the number of working cycles N of PR w load in given conditions (load amplitude A, bath temperature T) are the basis for establishing the dependence of Young's modulus E(N) and composite bending strength $R_g(N)$ on the number of cycles N. Fig. 12 shows a demonstration result of sample p PG (A=35 MPa, T= 30°C, N= 4000) bending test (Fig. 12).

Demonstration regression functions achieved as a result of parameters estimation on the basis of selected set of strength measurements - relative elasticity model and relative bending strength, are shown on Fig. 13 and Fig. 14.

Similarly as in case of PN research, the results of experimental tests PG will be used for identification of parameters of numerical simulation procedures for the degradation process embracing the mechanism of defects generating in the aspect of model characteristics compatibility with those experimentally established. Diversified strength condition on sample thickness in bending conditions makes additionally the basis of assessment of diversification of density distribution of defects on thickness PG.

a)

b)

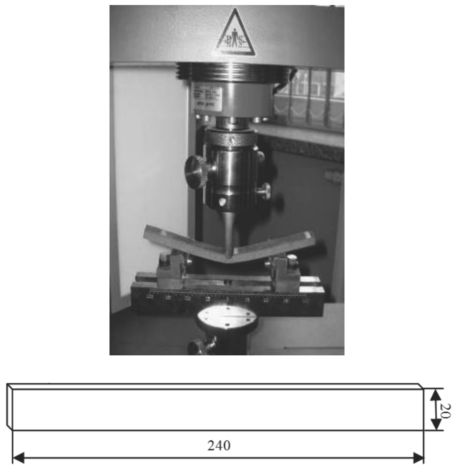


Fig. 11. The view of the working station for establishing bending characteristics PG (a) and samples measurements (b)

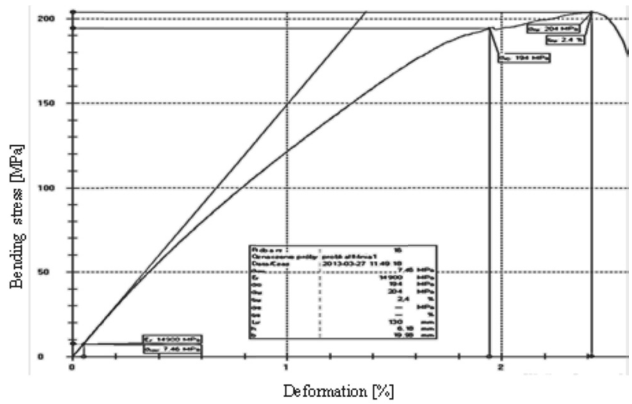
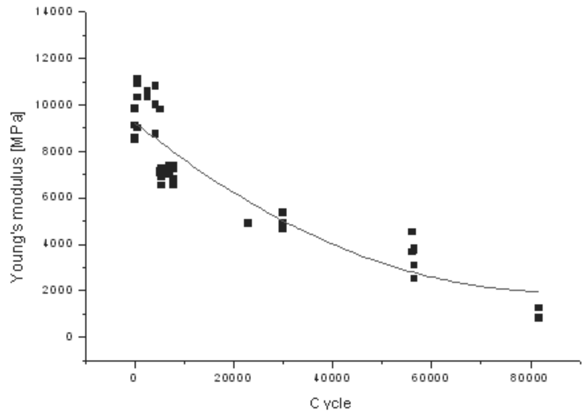


Fig. 12. Demonstration result of sample PG (A=35 MPa, T=30°C, N= 4000) bending test

2.5. Establishing thermal characteristics of material samples in condition corresponding to selected number of strength cycles with the application of contact method

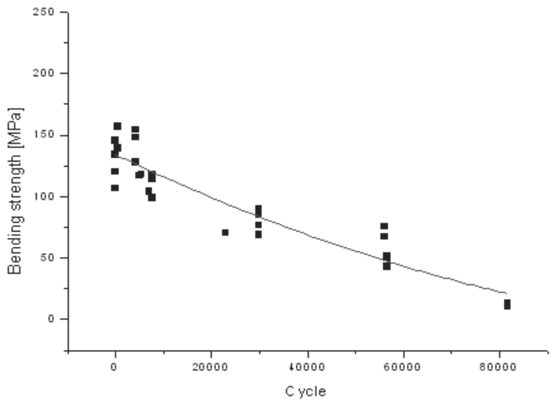
The research program predicts making research from randomly selected part PR of PC samples to establish thermal conductivity coefficient λ by means of contact method and specific heat c by means of contact and calorimetric methods. Fig. 13 and Fig. 14. shows the view of demonstration sample PC and measurements. Fig. 15 shows the schema of measurement system of thermal conductivity coefficient. In order to identify the parameters of diagnostic relation, mentioned in chapter 2.3, allowing the establishment of thermal characteristics of material PR on the basis of results of non-destructive tests on individual stages of load process, similar to those conducted on PR, described in chapter 2.3, research with the application of thermal imaging method, PC are subjected to. The system and the principle of measurement are identical to presented in Fig. 16 with reference to PR.



Model	Polynomial
R Value	0.9088

Young's Modulus	Intercept	Young's Modulus	Intercept
	B1		B1
	B2		B2

Fig. 13. Demonstration regression functions as a result of Young's modulus measurements E(N) for a selected set PG



Equation	Polynomial
R value	0.93882

Bending strength	Intercept	Bending strength	Intercept
	B1		B1
	B2		B2

Fig. 14. Demonstration regression functions as a result of bending strength $R_g(N)$ for a selected set PG

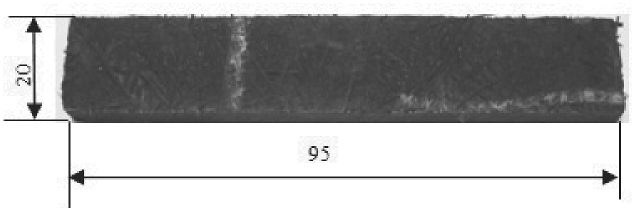


Fig. 15. The view of demonstration sample PC

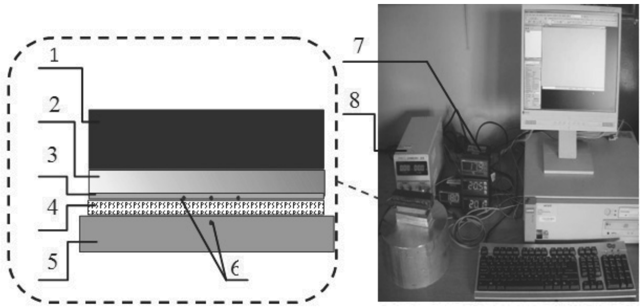


Fig. 16. Measurement system of thermal conductivity coefficient system;1 - downforce, 2 - insulation, 3 - heater with a layer of silicone, 4 - sample, 5 - radiator, 6 - thermocouples, 7 - thermometers, 8 - power pack

Established thermal characteristics will be used for the verification of simulation model of material fatigue-ageing process.

3. Simulation model for the analysis of fatigue-ageing destruction process and the assessment of residual strength of composite pipes

The developed simulation model of fatigue-ageing processes [21,22, 29-32), for the purpose for the assessment of residual strength of composite pipes takes as basis the model of composite material of the pipe in its initial state [1,23]. This model is then subjected to the sequential procedure of structural and parametric modification, which complies with experimentally recognized symptoms of degradation process, the measure of which we assumed the changes described in chapter 2 diagnostic characteristics: transition time t_p of acoustic wave, Young's modulus E(N), and flexural stiffness [2,20,22]. Thermal characteristics, such as conductivity factor λ and specific heat c, are used for verification of the model and recognition of destruction mechanism of the material. Simulation generated boundary state, as a result of load by the boundary number of cycles N_g, corresponding to fatigue strength for tested load parameters (A, T):

$$R_m(N_g)=0, \tag{1}$$

$$N_g= Z, \tag{2}$$

is the additional correctness criterion of simulation model.

3.1. Model of composite pipe material

The developed model of composite material embraces cuboidally estimated section of pipe. The characteristics of the centre of volume elements correspond to the polyester matrix. Properties of the boundary layers reflect, including directionality features of the strengthening structure, elastic properties of individual layers of fibres.

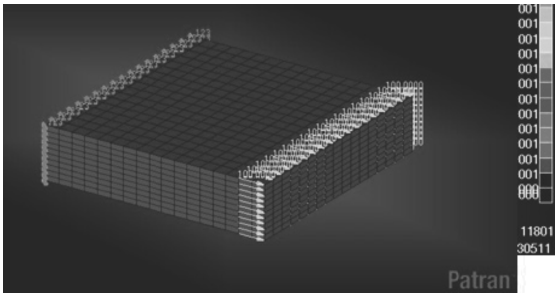


Fig. 17. The structure of computational model with boundary conditions corresponding to circumferential tensile

a)

b)

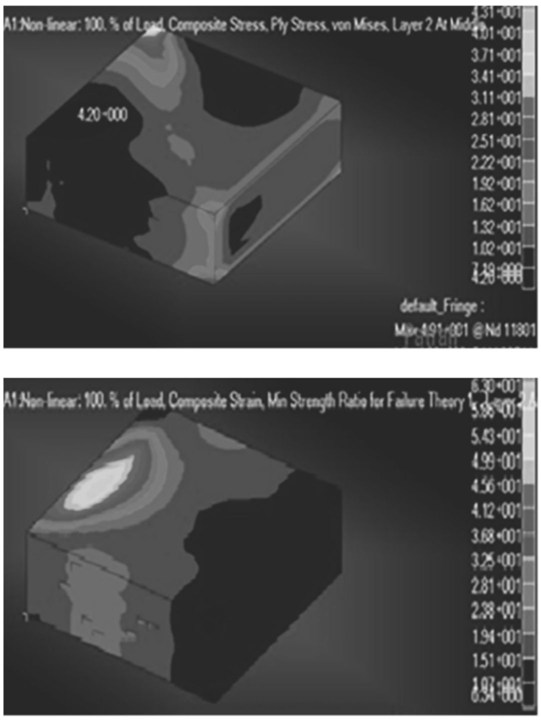


Fig. 18. Demonstration solution corresponding to the distribution of reduced stress of the model in external layer (a) and the middle of the first layer of volume elements (b)

The model is subjected to static analysis with the unit intensity in order to establish the distribution of internal loads - initially assumed lack of defects means the solution corresponding to homogeneous state. The shape of demonstration solution corresponding to the distribution of model reduced stress for the steady load distribution in the cross nodes on axial components, in external and middle plane of the first layer of volume elements is shown in Fig. 18.

3.2. Procedure of model modification in the procedure of simulation of composite destruction

The result of the analysis of the state of stress, particularly with reference to average stress in fiber cross-sectional planes and static in middle planes of element layers (interlaminar shear surfaces) is taken as the basis for random procedure of defects generation, which in numerical realization corresponds to release of neighbouring nodes of elements from ties compatibility of displacements in proper directions. The probability of ties elimination depends on proper component of stress, the step size procedure corresponding to the number of load cycles and coefficients corresponding to the parameters of fatigue-ageing process (A, T). The modified model is subjected to another analysis which corresponds to next steps of the fatigue-ageing load process of the material. The shape of the result of the next analyses of modified model in other conditions as it is shown before in Fig. 19 and Fig. 20.

a)

b)

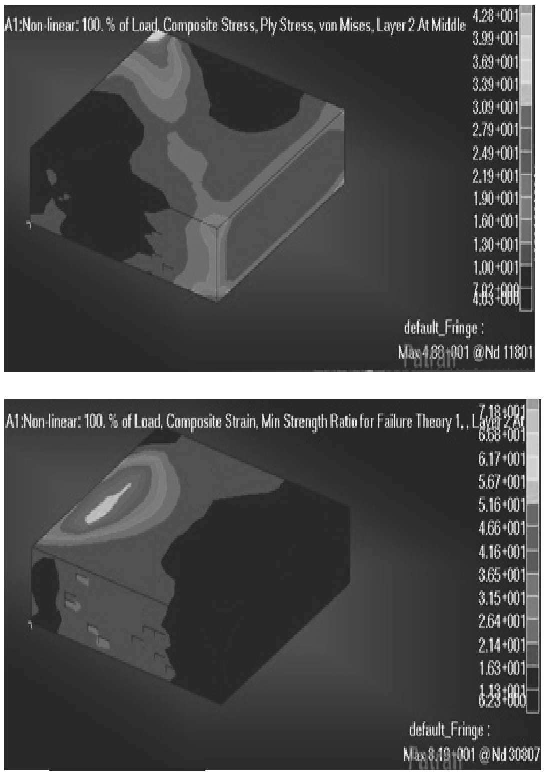


Fig. 19. The solution corresponding to the distribution of reduced stress of modified model in external layer, a) and the middle of the first layer of volume elements, b) with 5% of damaged elements

a)

b)

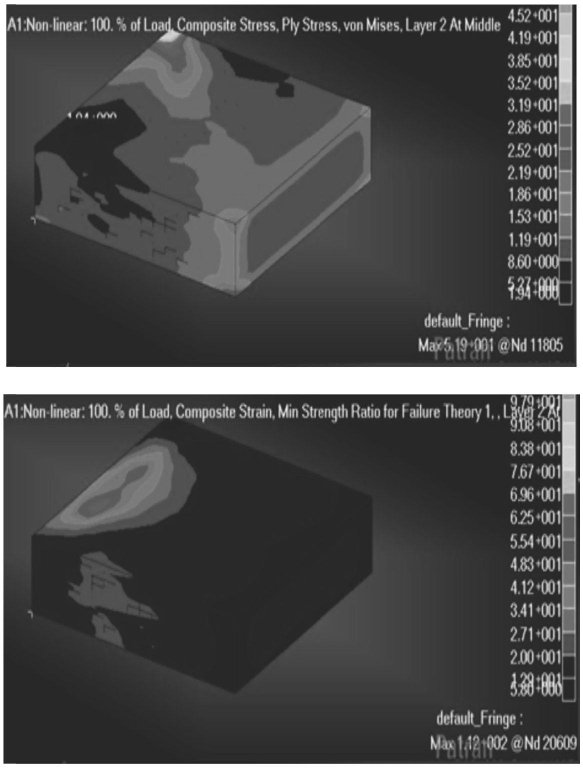


Fig. 20. The solution corresponding to the distribution of reduced stress of modified model in the external layer, a) and the middle of the first layer of volume elements, b) with 10% of damaged elements

The result of the demonstration showed that simulation procedure is a model, the assessment of which is conducted on the basis of thermal characteristics established in the way described in chapter 2.

Table 2.
Physical properties of the composite

Ingredient	Polyester resin	Fiberglass	Water
Young's module, E [GPa]	3.43	66.5	-
Kirchoff's module, G [GPa]	1.27	27.0	-
Poisson Factor, ν	0.35	0.23	-
Density, ρ [kg/m³]	1250	2250	1000
Specific heat, c [J/kg·K]	1400	729	4190
Thermal conductivity factor, λ [W·m⁻¹·K⁻¹]	0.20	1.04	-

3.3. Identification of the state of simulation model

The compliance criterion of the achieved simulation result with experimentally established strength characteristics PR constitute strength and physical characteristics of the material. The material with the generated defects in the initial phase of the process, when locally unstable concentration of defects is not observed, should meet the criterion of compatibility of elastic properties - Young's modulus and Poissone's number with its changes resulting from the degradation process. The investigation of the elasticity module changes provides then the basis for drivers selection a, b, c of structural modification procedure, i.e. the way, in which the probability of elimination of ties corresponding to delamination p_d and fibres tearing p_z, depends on amplitude A, the number of cycles in the next step of load ΔN and possibly the bath temperature T.

$$p_d(A,\Delta N,T) = a_d A + b_d\Delta N + c_d T \,, \qquad (3)$$

$$p_z(A,\Delta N,T) = a_z A + b_z\Delta N + c_z T \qquad (4)$$

In case of knowing the expected number of cycles, after which the exhaustion of carrying capacity of shell boundary state criterion occurs, transgression of the level of destructive stress in the matrix may occur - the plasticity of the coating thickness is equivalent to the loss of the pipe integrity. The possibility of achieving the satisfying compliance of destructive number of cycles according to the criterion, the softening of matrix enables the identification of another constant in relation (3) giving it non-linear character:

$$p_d(A,\Delta N,T) = a_d A + b_d\Delta N + c_d T + d_d\Delta N^2 \qquad (5)$$

The additional criterion for assessment of model's compliance might be the thermal characteristics of the composite. In order to achieve this we can formulate a hypothesis, that their changes are substantially connected with the density of defects with the character of delamination. In case of genuine material it means the increase of water absorption and connected with that the change of specific heat and conductivity factor. Introducing the degree of filling the delamination with water as a result of composite impregnability r, using the method of weighted average, we can express:

$$c = s\, c_w + (1 - s)\, c_k \qquad (6)$$

$$\lambda = s\, \lambda_w + (1 - s)\, \lambda_k \qquad (7)$$

where: $s = r\zeta$, ζ is delamination density, factor k represents composite, w - water.

Value r is calculated on the basis of experimentally established content of water s in composite and delamination density ζ achieved as a result of applying formulas (5) or (6), (7) of simulation procedure. In Table 2 we juxtaposed the physical properties of composite ingredients. The algorithm of the process of virtual diagnostics simulation in [35] is presented.

4. Conclusions

Within the work we presented the basis for experimental research conducted in order to identify the parameters and drivers of diagnostics simulation procedure of polyester/glass pipes in fatigue-ageing conditions. The purpose is developing the tool of virtual diagnostics simulation which enables the assessment of the degree of exhaustion of carrying capacity of composite pipes in condition of numerical models research. The key of achieving the durability assessment or residual strength of composite elements is the pointed possibility of their calculation on the basis of correctly built model. The basis of assessment in numerical model provides the strength analysis of the model generated with the use of developed simulation procedure taking into account the history or prognosis of the exploitation program of composite element. The reliability of the model is increased by compliance of coupled strength, acoustic and thermal properties. The acoustic and thermal characteristics, as independent tools of correctness verification of the model, enable the simulation, for example, processes of acoustic wave propagation of thermal process reflecting the virtual diagnostic processes. The characteristics of these processes provide the independent basis for assessment of material condition with the use of appropriate diagnostics relation of residual strength $R_m(N)$ as well as the speed of acoustic wave propagation of proper thermal properties (thermal conductivity, diffusivity).

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