ISSN 2409-9066. Sci. innov. 2017, 13(5): 53—62 https://doi.org/10.15407/scine13.05.053

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HARDWARE AND SOFTWARE COMPLEX TO DETERMINE THE STRENGTH PARAMETERS OF COMPOSITE MATERIALS AND STRUCTURAL ELEMENTS OF ROCKET AND SPACE EQUIPMENT

A hardware and software complex has been developed to determine the strength parameters of promising carbon fiber reinforced polymers and structural elements of rocket and space equipment under different mechanical loads within the operating temperature range. The developed complex components, in particular, the multi-channel data-measuring systems and the appropriate software for measurement, acquisition of experimental data, and calculation of strength parameters of such materials have been described. The complex capacity and effectiveness have been tested.

Keywords: carbon fiber reinforced polymer, composite materials, strength, deformation, and data-measuring system.

Over the past few decades, the use of various composite nonmetallic materials has been growing significantly. This is true also for carbon-plastic composite materials that are increasingly used in rocket-space and aircraft engineering [1, 2] due to unique properties of carbon plastics, in particular, their high specific strength and rigidity, low temperature expansion, and corrosion resistance. Unlike metals, the composite materials are essentially heterogeneous and anisotropic [3], which requires more physical parameters (stress, strain, displacement, etc.) to be controlled when testing them. In this case, measurement, visualization, and accumulation of experimental data obtained in real time with the use of modern computer systems are necessary. Unfortunately, the existing hardware for testing the structural materials designed and manufactured in the past century mainly does not meet the present-day needs. In addition, the processing of primary test data and the determination of composite material strength parameters are quite specific processes that shall be carried out in accordance with specially developed standards.

It should be noted that the carbon fiber or fiberglass technology and, accordingly, the structure of standard specimens for strength tests and that of product material can vary significantly. Therefore, in addition to calculating the strength and bearing capacity of specific products made of carbon-fiber composite materials using the data on elasticity and durability obtained from the tests of standard specimens, the rocket and space technology corporations conduct field tests of such products, which are expensive, complicated, and time consuming process.

To reduce the scope and to increase the informational efficiency of costly field tests, it is possible due to production of the most relevant elements and smaller model structures manufactured using similar technology with their subsequent mechanical tests under similar stress schemes. This would enable comparing the strength and elasticity of specimens and models and developing a method for more reliable calculation of strength and bearing capacity of structures made of composite materials. The absence of multichannel information and measuring systems (IMSs) as part of standard or specially designed test facilities or stands makes it impossible to conduct tests of models and structural elements made of composite materials and to obtain the necessary experimental data. This complicates calculations of the design parameters of critical elements of rocket and space engineering structures.

To address the above-mentioned problems, a specialized hardware and software complex has been developed and created, which enables the mechanical tests of both standard specimens and elements of structures made of composite materials and the determination of appropriate durability characteristics. The created complex includes multi-channel information measuring systems FpTiraTest-1901 and PMX-Test for testing the specimens and structural elements of composite materials, respectively, as well as special software for measurement and accumulation of experimental data, and for calculation of strength parameters of these materials.

INFORMATION AND MEASURING SYSTEM FpTiraTest-1901

In order to automate the measurement and recording of experimental data during testing of composite materials on standard test facilities, in particular, FP 100/1 and TIRAtest-2300, data acquisition modules USB 1901 (ADLINK Technology Inc., Taiwan) (Fig. 1) have been used; 1901 USB module has 16 analog inputs, provides discrete analog-to-digital conversion: 16 bits at a frequency of up to 250,000 samples per second; it is connected to the outputs of regular test measuring systems FP100/1and TIRAtest-2300. Totally, IBC FpTiraTest-1901 has 4 channels for

Fig. 1. Data accumulation module USB 1901(ADLINK Technology Inc.)

measurement and record of experimental data: the first one is for measuring stress, the second one is for measuring test machine traverse displacement, the third and fourth ones for measuring strain (for instance, tensile strain or compression). The input physical values, including stress, displacement, and strain are converted using measuring devices that are part of FP 100/1 and TIRAtest 2300, standard stress converters, traverse displacement sensors, and some resistive strain sensors for measuring strains using strain-gauge station 4ANCH-22. The mentioned IMS can be used at other test facilities and machines. For its operation appropriate FpTiraTest software with characteristics listed below has been developed.

PMX-TEST INFORMATION AND MEASURING SYSTEM (IMS)

While for testing the specimens of composite materials it is sufficient to have IMS with at least, four channels, testing the elements and models of structures made of these materials requires multichannel IMS. Taking into account an advantageous price-technical quality ratio of the system, PMX modular measuring amplifier system [4] by HBM (Germany), a well-known manufacturer of various measuring devices and systems, which has a rich experience in their application in vari-

ISSN 2409-9066. Sci. innov. 2017, 13 (5)

ous industries, has been selected as base unit for the designed multifunctional IMS. The advantages of PMX system include high precision, reliability, applicability to industrial scale, the use of special high-quality measuring technology from HBM, the ability to increase the total number of measurement channels by connecting multiple PMX systems to one computer.

The PMX system includes a basic device (WG002) containing a case, communication connectors with indicators, and 4 slots (on each, a four-channel measuring card can be installed). Thus, the maximum number of channels for one PMX system is 16. When choosing the cards, the conditions for the implementation of multichannel strain measurements and availability of several channels for measuring stress parameters (stress, pressure) were met. To this end, the PMX is equipped with PX-455 (3 pcs), measuring cards (modules), and PX-401 card (1 pc.). The measurement card PX-455 is used to connect full/half-bridge strain gauge and inductive transducers, as well as piezoresistive and potentiometric sensors. The measuring card PX-401 is for input and further transformation of direct current and voltage analog signals. It can be connected to the stress and/or pressure sensors that have an output signal in the form of a constant voltage or direct current or directly to test machine or bench output signals proportional to the stress parameters.

Insofar as the PMX system does not allow for the connection of any temperature converters, to measure temperature a separate five-channel MIKRA-5 system has been developed and manufactured based on MIKRA I3 programmable indicator of process parameters (Ukraine).

The appearance of a small PMX-TEST IMS designed to test the strength/durability of structural elements and models made of composite materials is presented in Fig. 2. The PMX-TEST block diagram is shown in Fig. 3. It comprises a system (12 channels) for measuring strains and loads, in particular, pressure and stresses (4 channels) and a temperature measurement system MIKRA-5 (5 channels).

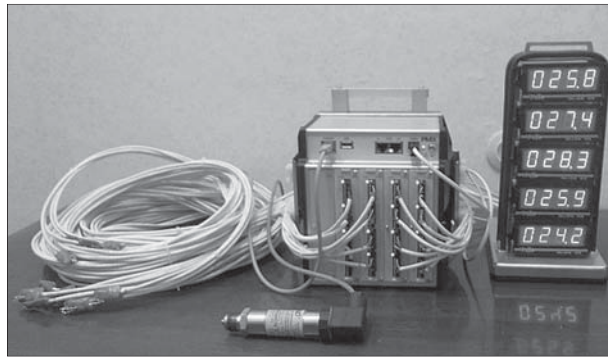


Fig. 2. External view of IBC PMX-TEST

The strains are measured using three PX-455 four-channel cards to which ε1..ε12 strain gauge transducers are connected via cables and interfaces. The mentioned above loads are measured using four-channel measuring card PX-401. PMX IMS is connected to PC via Ethernet, while MIKRA-5 temperature measuring system is connected via serial USB using USB/RS-485 AC-4 converter.

The strains of tested object surface are measured in each of 12 measuring channels using a strain gauge with a nominal resistance of 200 or 400 Ohm. To realize the half-bridge circuit, special interfaces/adapters comprising additional precision resistors are used. To measure load (stress, pressure) when testing elements and models of structures made of composite materials, any measuring converters that ensure output current signal ranging within 4—20 mA or 0—20 mA can be used. The described IMS contains pressure converters of two types: PC-28 (APLISENS, Poland) and SEN-8601 (KOBOLD, Germany) of the same structural design. The output current varies from 4 to 20 mA, with maximum range of measurements being from 0 to 50 MPa. The limit reduced error for PC-28 and SEN-8601 pressure converters is ±0.2%, and ±1%, respectively.

The temperature measuring system was designed with the following factors taken into consideration: low output signal quantity of existing thermoelectric transducers, which usually does not exceed 50 mV, necessity of output signal linearization, temperature of cold thermal junction, possibility of stand-alone operation and transfer of measurement results to PC. Proceeding from the above considerations, MIKRA I3 (Ukraine) programmable indicator of process parameters has been selected. It ensures the measurement and indication for a wide range of thermoelectric transducers and data transfer via RS-485 interface using open protocol Modbus RTU [5]. The designed MIKRA-5 system for temperature measurement includes 5 independent channels, each having MIKRA I3 programmable indicator.

PMX-TEST-MONITOR PROGRAM

To operate the PMX system [4], HBM has developed MBX Web Server software that is specially designed for the initial configuration of system's channels, primary signal processing, and for simple visualization of data received. This software enables to set the initial parameters for each channel of the system individually, namely, to select the type of input instrument converter (full bridge, half-bridge etc.), to set the linear signal conversion function, to reset the initial signal, as well as to set the filter type (Bes-

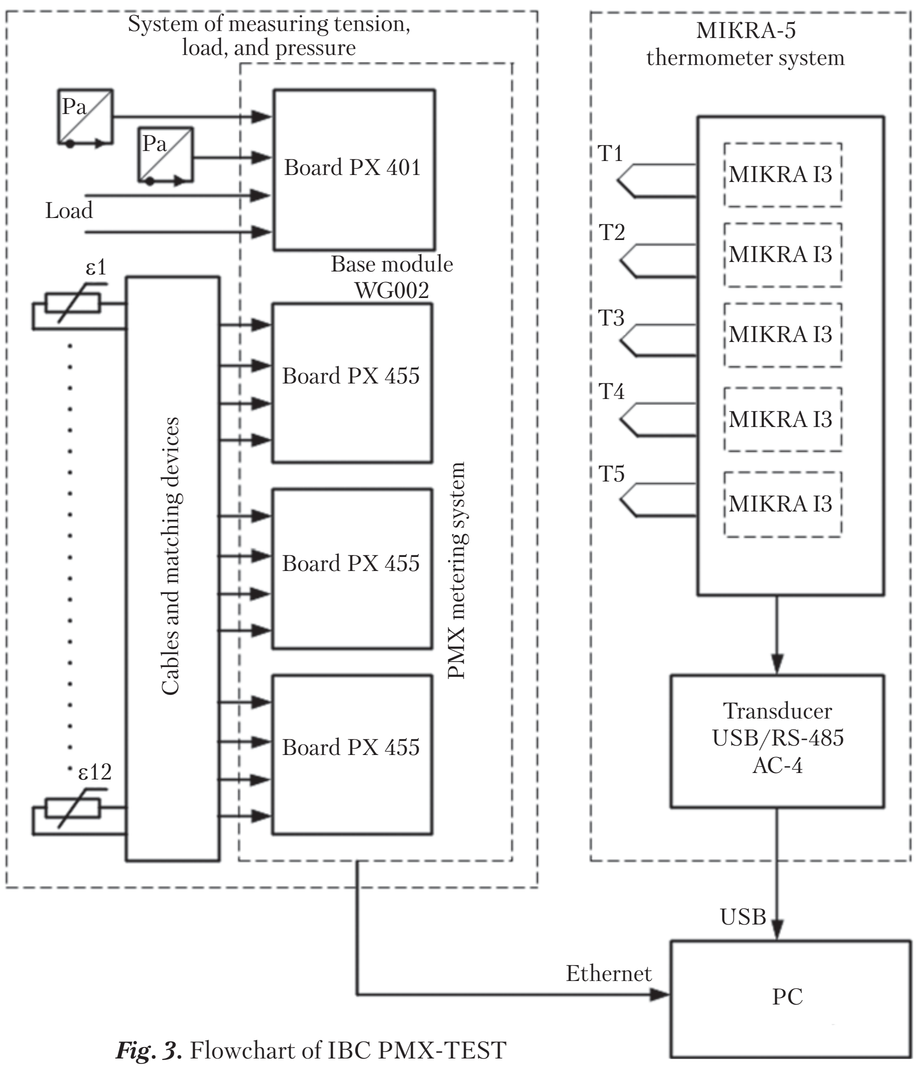


Fig. 3. Flowchart of IBC PMX-TEST

sel, Batherworth) and its frequency in each measurement channel. The disadvantages of Web Server PMX software are slow display of results and limited graphical visualization and data storage capabilities.

To ensure the joint operation of PMX and MIKRA-5 measuring systems, as well as to enhance the functionality of presentation and processing of experimental data, a single PMX-TEST-Monitor program has been created. The main requirements for it were convenient and intuitive use of its main elements, real time data visualization in both digital and graphical forms, accumulation and storage of experimental data on PC. The creation of single PMX-TEST-Monitor program was possible due to the fact that the IMS operates using a well-known Telnet network protocol [6], while the MIKRA-5 system uses data exchange via the Modbus RTU open communication protocol [5]. These protocols are the basis for data exchange between PMC-TEST and PC.

The graphical interface of PMX-TEST-Monitor program is shown in Fig. 4. For convenience, all measuring channels are grouped by type of physical value measured: groups of channels for measuring strain (D1..D12), group of channels for measuring loads (pressure, stress — P1..P4), and group of channels for measuring temperature (T1..T5). The graphical interface is divided into two parts along vertical extent. In its upper left part, there is the control panel that runs IMS PMX-TEST, starts and ends data accumulation, indicates current time and number of experimental data counts. Nearby, on the interface, there is the load P1..P4 view bar (stress, pressure, etc., totally 4 channels) and to the right, in the upper part, there is the temperature T1..T5 view bar (5 channels). In the lower part of PMX-TEST-Monitor graphical interface, there is the strain D1..D12 view bar (12 channels). For convenient visualization, the view bar of strains measured contains a graphic window displaying measurement results from all channels as bar chart, in its left part (Fig. 4). Each of 21 measured values is displayed both digitally on the respective indicator and graphically on time chart in real time.

PMX-TEST-Monitor program ensures performance of wide range of user's functions, in particular, setting of measuring channels including units, conversion factor, zeroization of initial signal for each channel, flexible scale setting along the axes of time diagrams, setting of parameters for display of both digital data and graphical images. The program ensures storing the accumulated experimental data by their record to text file with extension «*.csv». This enables their further analysis and processing in MS Excel, Origin, etc.

FpTiraTEST PROGRAM

FpTiraTest program ensures measuring stresses, strains, displacements in real time in the course of tension, compression, and bending of specimens made of composite carbon plastic materials, as well as accumulating and storing experimental data for their further processing. In terms of physical values measured and stored the program is harmonized with standards ASTM D 3039 [7], ASTM D695 [8], ASTM D 7264 [9], which regulate testing (tension, compression, and bending) of composite materials with plastic matrix.

FpTiraTest graphical interface is shown in Fig. 5. In the left part, there is the indication and measurement control panel that contains separate digital indicators for each measuring channel. Nearby, there are buttons for setting the zero value and the polarity of value measured. Below, there is an indicator of current test time and the number of counts (measurements) performed with the buttons for starting and stopping the accumulation of experimental data. Underneath, there are windows for inputting the maximum values for viewing the measured values as curves in the corresponding diagrams.

Most of the graphical interface is occupied by customized rollover pages. The «Test Description» page is intended for entering and saving the settings of measuring channels (name of physical value, units of measurement, conversion factor,

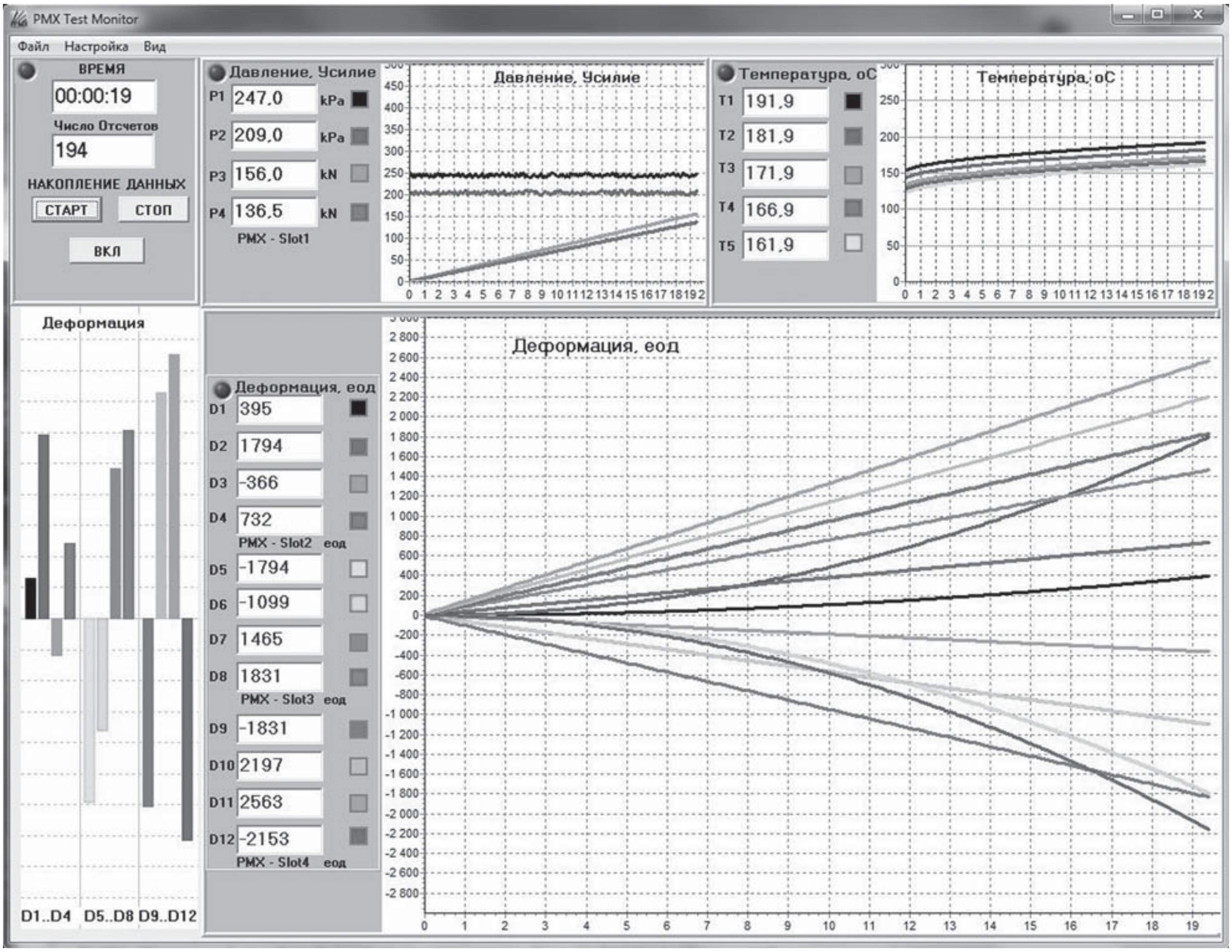


Fig. 4. Graphical interface of PMX-TEST-Monitor

number of digits after the decimal point in measurement result displayed for visualization), the experiment description (date of test, name of test facility, type and rate of load, etc.), and the specimen description (material, number, dimensions). All information contained on this page, after the test, is stored in experiment data file together with the arrays of values measured. For displaying the measured values in the graphic form, there are *Load Chart* and *Time Chart* pages. The *Load Chart* page shows the current stress on the Y axis and readings of other channels (strain, traverse displacement) on the X axis. On the *Time Chart* page, the X-axis indicates the current value of test time, and the Y axis represents the readings for all four values (stress, strain, displacement) measured. For viewing several different physical values with different maximums on the same axis, this axis is presented as range from 0 to 100% of maximum values set for each measuring channel. For a quick view of the arrays of data received, there is *Table* page. It presents all arrays of measured physical values (time, stress, displacement, and strain) in tabular form.

FpTiraTest program was developed in such a way as to take special measures for reducing the random components of measurement errors caused by effect of electrical or electromagnetic interference from the industrial AC network operating at a frequency of 50 Hz. To this end, the

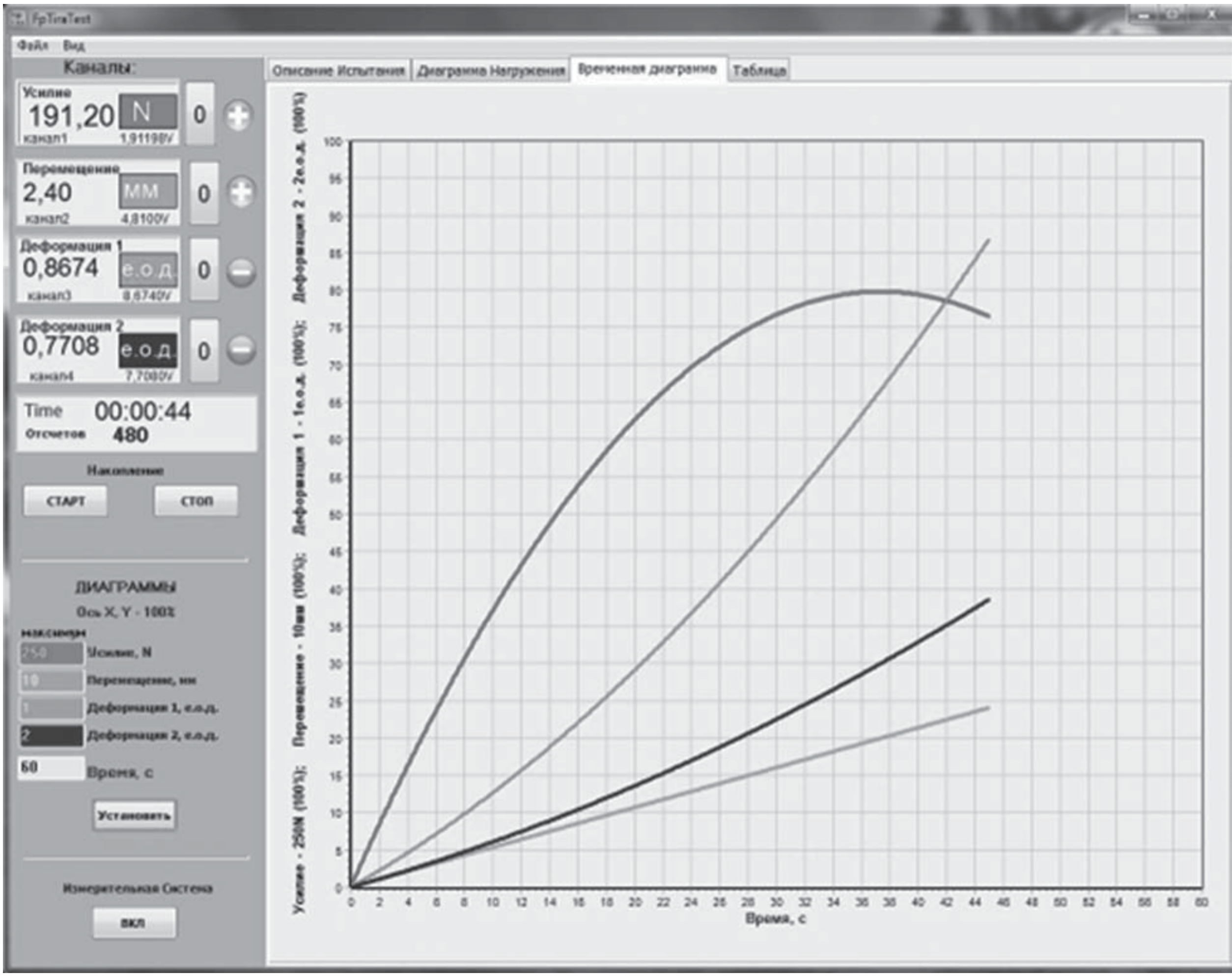


Fig. 5. Graphical interface of FpTiraTest

frequency of measurement on all channels is set as high as possible, with the measurement result for each channel defined as the average over the time interval divisible by the alternating current period.

CFRP STRENGTH PROGRAM

To computerize the calculations of strength and elasticity properties of carbon-plastic composite materials under tension, compression, and bending, a special program CFRP STRENGTH has been developed. The CFRP abbreviation means Carbon Fiber Reinforced Polymer. The program is designed to process primary experimental data obtained from mechanical tests of specimens made of composite materials using the FpTiraTest program or similar one. It also provides statistical data processing using the two-parameter Weibull distribution. It should be noted that tension, compression and bending tests are the most common and informative tests for carbon-fiber composite materials and enable not only measuring the strength but also the production of strain diagrams for the material with determination of appropriate parameters.

The program starts with opening and reading the file with original experimental data. The program provides reading of plain text files with extensions «*.csv» or «*.txt». It is also possible to transfer the initial data from open books in MS Excel, Origin, etc. to the program by «Copy-Paste» method.

The program provides preliminary processing of original experimental data, namely, the performance of the most frequently used processing procedures, in particular, linear transformation of the input data array via a separate channel into the output array of a particular physical quantity. Usually, the recorded original data have a significant random error associated with the effect of arbitrary interference or if a measurable value is significantly lower than the nominal measurement range. The error random component can be reduced by finding the average value of individual measurement results. CFRP STRENGTH program performs the simple moving average function, which enables averaging the array of original data.

The mechanical characteristics of composite carbon fiber materials in this program are computed taking into account the requirements of standards [7—9]. The tensile, compression, and bending strength is determined based on the specimen size according to the known formulas presented on the CFRP STRENGTH graphical interface (Fig. 6). The most difficult and labor-intensive calculation of carbon-plastic composite materials mechanical characteristics is the calculation of elastic modulus. Therefore, the CFRP STRENGTH program contains special procedures to simplify the calculations. To this end, the program interface panel has two sliders to set the initial and final relative strains (Fig. 6, *b*), among which the elasticity module will be found. ASTM D 3039 standard [7] recommends the initial and final relative strains to be equal to 0.001 and 0.003 m/m, respectively. The elastic modulus is calculated by the program using the least squares method.

Having obtained the material mechanical characteristics for a single specimen, CFRP STRENGTH provides the data accumulation in a separate datasheet and the subsequent standard statistical processing of the test results, namely, the estimation of average mean for each value, its standard deviation and variation in accordance with standards [7-9]. The calculation results can be saved as a text file with extension «*.csv» or exported in tabular form via the clipboard into a MS Word or MS Excel document.

An important feature of the CFRP Strength program is the ability to calculate the parameters of two-parameter Weibull distribution. This distribution is often used for statistical estimation of material strength. This distribution is considered to describe well the strength distribution of individual carbon fibers and carbon bundles, and the results of fatigue tests for composite materials with a plastic matrix [10]. In addition, the Weibull two-parameter distribution is also used for the statistical estimation of the strength of specimens from composite carbon-plastic materials for different types of mechanical load.

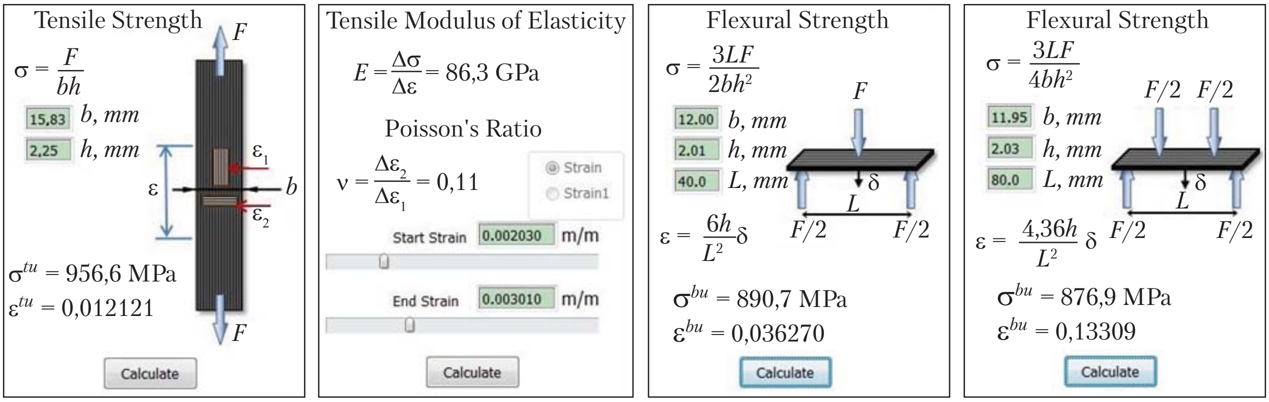
TRIALS OF THE COMPLEX

Using the developed hardware and software complex for measuring the strength parameters of composite materials and elements of rocket and space engineering structures, a batch of specimens of new promising carbon-plastic material manufactured at *Pivdenne* Design Office has been tested. The specimen strength and elasticity while bending at a room temperature and at 200 °C have been determined. It has been established that the obtained characteristics have a little scatter and remain high as temperature increases to 200 °C.

Model shells from a new carbon-plastic composite material made at *Pivdenne* Design Office have been tested on the original trial equipment using the created complex, at the Pisarenko Institute of Problems of Strength of the NAS of Ukraine. Tension, compression, internal pressure and combined load tests have been carried out in the range from ambient temperature to 300 °C.

The tests have shown that the software complex created with the use of modern measuring equipment provides multichannel measurement

ISSN 2409-9066. Sci. innov. 2017, 13 (5)



a *b* *c* *d*

Fig. 6. Parts of CFRP STRENGTH interface for measuring strength and elasticity modulus under stretching (*a, b*); bending strength (*c, d*)

of strains, displacements, and load parameters while testing the materials and elements of structures from composites. Its software performs all necessary functions, in particular, high-precision measurements, visualization, accumulation, storage and processing of experimental data and has a convenient and intuitive interface.

The use of complex has enabled obtaining important physical and mechanical properties of shell material and comparing them with specimen ones. The obtained important mechanical properties of tested carbon plastics will be used for making and adjusting the design calculations of important elements of rocket and space engineering structures.

CONCLUSIONS

Based on the terms of reference, a pilot hardware and software complex for measuring the strength parameters of promising composite materials and elements of rocket and space engineering structures under various mechanical loads within working temperature range has been designed in cooperation with *Pivdenne* Design Office.

As a results, hardware complexes IBC FpTiraTest-1901 for testing specimens under tension, compression, and bending and IBC PMX-TEST for testing strength of models and elements of structures made of composite materials have been designed.

FpTiraTest and PMX-TEST-Monitor software for recording, visualizing and storing the original experiment data related to the tests of specimens and elements (models) of composite material structures as well as CFRP STRENGTH program for measuring strength and elasticity of the mentioned materials have been developed.

All components of created complex have been tested. The test results have shown their effectiveness and ability to perform the tasks assigned.

Important physical and mechanical properties of carbon plastic composite materials of the specimens and model shells have been obtained, which can raise effectiveness and reliability of design calculations for the critical elements of rocket and space engineering structures and reduce the scope of their field tests.

In the view of availability of unique test facilities at Pisarenko Institute for Problems of Strength of the NAS of Ukraine, which enables to test both the specimens and the structural elements under various thermal and mechanical loads within working temperature range it is expedient to continue the joint use of the complex both at the Institute and at *Pivdenne* Design Office.

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Received 12.05.17

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АПАРАТНО-ПРОГРАМНИЙ КОМПЛЕКС ДЛЯ ВИЗНАЧЕННЯ ПАРАМЕТРІВ МІЦНОСТІ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ І ЕЛЕМЕНТІВ КОНСТРУКЦІЙ РАКЕТНО-КОСМІЧНОЇ ТЕХНІКИ

Розроблено апаратно-програмний комплекс для визначення параметрів міцності перспективних вуглепластикових композиційних матеріалів і елементів конструкцій ракетно-космічної техніки за різних видів механічного навантаження в робочому діапазоні температур. Наведено характеристику складових частин створеного комплексу, а саме багатоканальних інформаційно-вимірювальних систем відповідного програмного забезпечення для вимірювання, накопичення експериментальних даних та виконання розрахунків параметрів міцності таких матеріалів. Виконано тестові випробування комплексу, що довели його працездатність та ефективність.

Ключові слова: вуглепластик, композиційні матеріали, міцність, деформація, інформаційно-вимірювальна система.

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АППАРАТНО-ПРОГРАММНЫЙ КОМПЛЕКС ДЛЯ ОПРЕДЕЛЕНИЯ ПАРАМЕТРОВ ПРОЧНОСТИ КОМПОЗИЦИОННЫХ МАТЕРИАЛОВ И ЭЛЕМЕНТОВ КОНСТРУКЦИЙ РАКЕТНО-КОСМИЧЕСКОЙ ТЕХНИКИ

Разработан аппаратно-программный комплекс для определения параметров прочности перспективных углепластиковых композиционных материалов и элементов конструкций ракетно-космической техники при разных видах механического нагружения в рабочем диапазоне температур. Приведена характеристика составных частей созданного комплекса, а именно многоканальных информационно-измерительных систем и соответствующего программного обеспечения для измерения, накопления экспериментальных данных и выполнения расчетов параметров прочности таких материалов. Выполнено тестовые испытания комплекса, которые показали его работоспособность и эффективность.

Ключевые слова: углепластик, композиционные материалы, прочность, деформация, информационно-измерительная система.