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Fatigue testing devices in a complex load condition

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ABSTRACT

Purpose: The article presents an overview of fatigue testing devices for polymer composites in a complex load condition. This paper presents physically existing devices and which are in the design phase. Also presented are own concepts of the construction of such devices. The analysis of each device was completed with a description of its advantages and disadvantages. There are various constructor approaches to the problem of fatigue testing. The choice of the device depends on the research program adopted for implementation.

Design/methodology/approach: The article presents the comparative analysis of individual devices. The authors presented their own proprietary designs of machines for fatigue tests in a complex load condition.

Findings: It was found that the selection of the machine should provide restoration of real working reconstruction of the tested object.

Originality/value: Specialist research machines are very expensive. Knowledge about technical solutions and potential capabilities of fatigue testing machines, and about the availability of such devices, allows for the best adjustment of the research program and the optimization of their costs. For designers of new machines, the submitted compendium of solutions may provide inspiration for improvements in the own constructions of subsequent generations of such devices.

Keywords: Research device, Fatigue life, Polymer matrix composite, Complex state of loads

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Comprehensive solving of the problem of fatigue life of vehicle load-bearing systems requires the use of various types of load-bearing structure tests depending on the design stage and the adopted implementation methodology. Various types of tests are possible. Due to the research object, the following tests are distinguished: complete vehicles tests, frame and body carriers tests, and finally standard samples tests. Forces that burden the object are divided into extortions: fixed, programmable and random. The tests can be carried out with simple and complex loads.

The use of polymer composites for vehicle load-bearing structures requires multi-stage fatigue testing due to their diversity and sensitivity to technology. In the first phase of the design process, fatigue tests are required on samples that are designed to determine the Wohler curves for the composite and the anticipated technology. Subsequently, the need for fatigue tests of nodes or sections of the supporting structure and entire objects appears. Complete load-bearing structures are usually subjected to fatigue testing when charging loads according to a program based on the schematization of a service spectrum representative of a given type of vehicle.

For fatigue tests in a complex state of loading of samples and sections of load-bearing structures, various types of devices are used [1-5]. Due to the manner of carrying out the load, we can distinguish devices: mechanical, resonant, hydraulic and electromagnetic.

The article presents an overview of more interesting solutions and presents a new device proposal, allowing to perform any spectrum of loads during such tests.

2. Fatigue strength test devices in a complex load condition

Devices for fatigue tests in a complex state of loads, due to various research problems, are always "made to measure". There is no agreed systematic classification of these devices. The general rule for all this type of machines is the possibility of simultaneously affecting the test sample with several extortions operating in different planes in the programmed cycles in one measurement test [6-8].

Samples on these devices can be simultaneously subjected to several of the following load combinations:

- bending with twisting,
- bending with stretching and twisting effects,
- twisting with stretching and twisting effects,
- bending with twisting and simultaneous tensile-twisting action.

Due to the way of impact and construction of machines, we distinguish between extortion occurring simultaneously or in a programmed sequence, in which each of the sequences can be programmed with respect to both force, amplitude and sequence of excitations. The division can also be done due to the way it affects the sample.

3. Vibrating device for fatigue strength tests using inertia forces

The device allows the test sample to be charged with a moment of bending and twisting that is acting in-phase. Such a case is considered to be the most unfavourable in the load bearing elements of vehicles. Diagrams of similar devices are presented in the paper [2]. The device was built to test the bearing elements of vehicles made of polymer composites. An inertia vibrator driven by a three-phase AC motor, controlled by a frequency converter, was used for enforcing loads. The maximum length of the tested element is 550 mm, frequency of excitations up to 50 Hz. The angles of deflections of inertial disks are approx. ± 2 %.

The general construction of the device is shown in Figure 1. The tested element is fixed in mounting brackets mounted on guides of semi-circular force elements. The guides are rigidly connected to the inertia discs. Sectional weights are mounted on the circumferences of the disks. An inertial vibrator driven by an electric motor is attached to the active disc. The horizontal component of the centrifugal force of the rotating masses of the vibrator (Fig. 2) causes the angular vibrations of the active disc. As a result of these vibrations, the tested element is loaded.

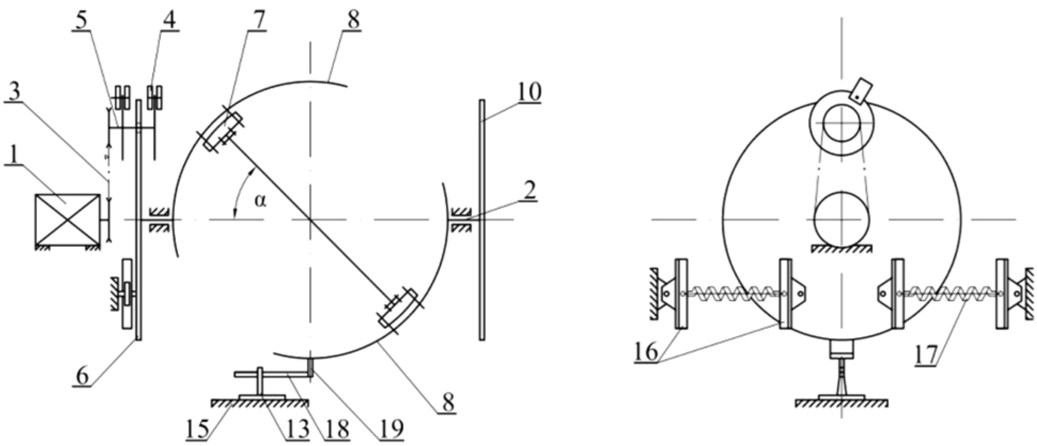

Fig. 1. Diagram of fatigue device: 1 – motor, 2 – main shaft, 3 – V-belt, 4 and 5 – vibrator weights, 6 and 10 – inertia disks, 7 – mounting brackets, 8 – semi-circular guides

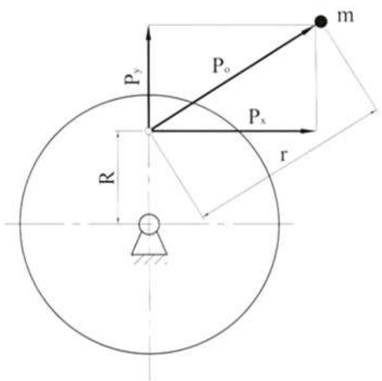

Fig. 2. Centrifugal force on the vibrator, m – mass of the weight, Po – centrifugal force, ν – frequency of the exciting force

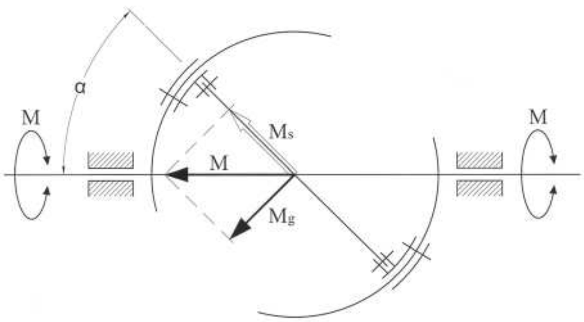

Fig. 3. Separation of the external moment depending on the angle of the sample setting

The use of semi-circular guides allows for arbitrary setting of the bending moment ratio to the torsional moment depending on the angle of mounting the sample in relation to the horizontal axis of the device ($0° \leq \alpha \leq 90°$). The distribution of moments loading the test sample is shown in Figure 3.

In the case where the flexural and torsional stiffnesses are identical, the moments are divided as follows:

$$M_g = M \sin \alpha \tag{1}$$

$$M_s = M \cos \alpha \tag{2}$$

The moment acting on the inertial disc can be calculated from dependency:

$$M_{(t)} = M_0 \cos \upsilon t \tag{3}$$

However, the centrifugal force and the moment in the oscillator describe the equations:

$$P_0 = mr^2\upsilon^2 \tag{4}$$

and moment $\mathrm{M_0 = P_0 \cdot R}$ (5)

3.1. Testing capabilities of the device

The inductor of the fatigue device is driven by a three-phase AC motor through a belt transmission. Rotational speed control is implemented using a frequency converter. The frequency of forces can be adjusted by changing the rotational speed of the motor, while the moment loading the tested element by changing the mass of weights fixed to the vibrator disc. The passive guide in the bottom part is connected by means of a flexible connector with the base of the device. The stiffness of the connector can be adjusted. Similarly, the active disc is connected to the base by coil springs and racks. The stiffness of the connection can be changed by changing the springs or their number. By means of changes in the stiffness of the connectors of both disks and their moment of inertia one can change the dynamic model of the device from a two-mass system with one natural frequency into a system with two natural frequencies. Below, in Figures 4, 5 and 6, the possibilities of loading the tested element are shown. Depending on the angle of inclination of the sample, different possibilities of its loading are obtained. From the load exclusively by tor through the complex load condition (bending and torsional moment) to the load only with the bending moment. The device thus allows for high-cycle fatigue tests of samples and structural components.

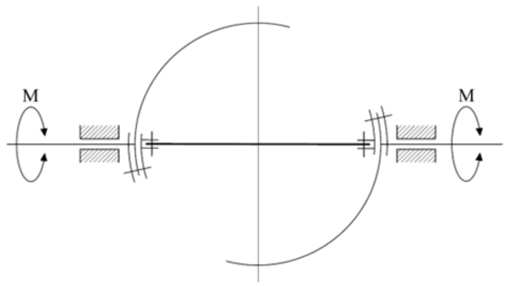

Fig. 4. The load with the torsional moment M_s

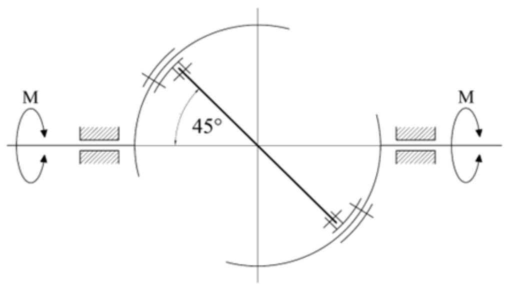

Fig. 5. In-phase load with the bending moment M_g and the torsional moment M_s

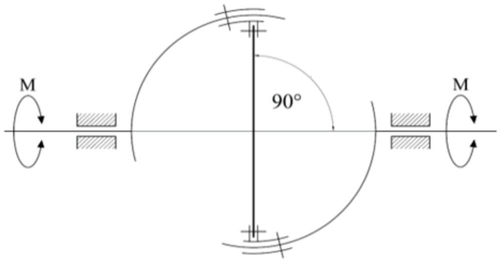

Fig. 6. The load with the bending moment M_g

The device has a simple and functional construction (Fig. 7). The dimensions of the device allow for the testing of large components (up to 550 mm in length). Many of them can even be tested on their real scale. A significant limitation of the device is the lack of the possibility of independent adjustment of the torsional moment and the bending moment. The device makes it possible to execute extortions with a strictly defined relationship of bending moment and the torsional moment. It depends on the angle of inclination of the sample in relation to the axis of the forcing shafts. The amount of the load and the frequency of forces can be adjusted by changing the engine speed and changing the mass of the rotating weights. Due to its construction, the machine may only make alternate cycles. There is no possibility of introducing extortions of pulsatory amplitudes, e.g. only positive or negative ones. In addition, the device performs extortions with a constant maximum value regardless of the degree of degradation of the tested elements.

Fig .7. The view of the device type ZP-1 with the mounted composite sample

4. Eccentric device for fatigue strength tests

Based on the experience gained at the Faculty of Mechanical Engineering of the University of Zielona Góra, a miniaturized version of the above-described machine was designed and built, designed mainly for testing fatigue strength on small samples. The device is shown in Figure 8.

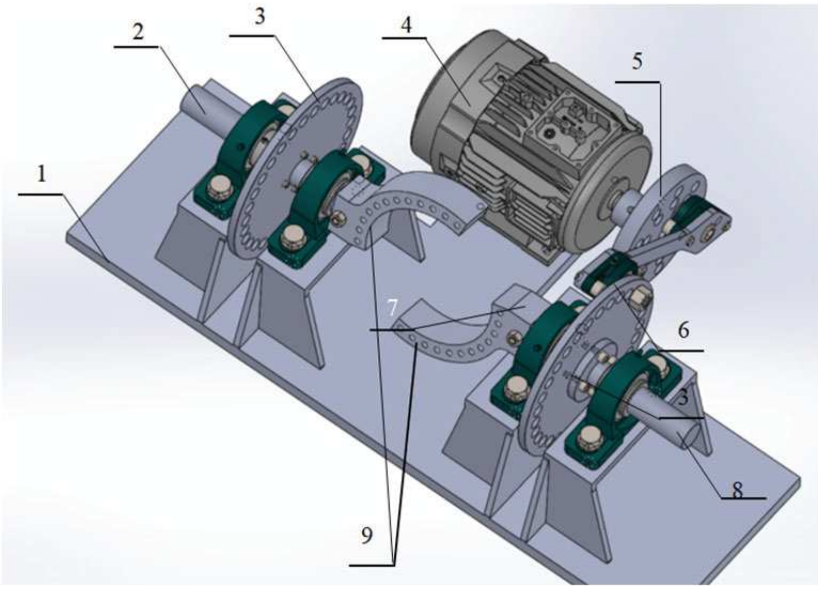

Fig. 8. The view of the fatigue machine – type WP-1 for tests in complex load conditions. 1 – base, 2 – shaft of the passive arm, 3 – inertia discs, 4 – motor, 5 – motor torque wheel, 6 – puller of the eccentric, 7 – weight of the vibrator, 8 – shaft of the active arm, 9 – semi-circular guides

The construction of the device is very similar to the construction of the device shown above. Several modifications have been made to the ZP-1 device. Firstly, the inertial extortions with the crank system has been replaced (items 6 and 7, Fig. 8). On the disc mounted on the motor shaft (7), the spiral holes for attaching the connecting rod head are drilled. By changing the diameter of the connecting rod head fastening and fixing its foot on the disk 3, it is possible to change both the forcing moment and the angle of twisting the sample. The method of fixing the samples has also been changed. The possibility of smooth adjustment of the angle of inclination of the tested sample has been abandoned. The construction of the designed device is currently in the final testing phase.

The WP-1 device implements a constant kinematic extortion. This means that regardless of the degree of degradation of the sample being tested, the angle of its twisting will be the same. Of course, as the degradation of the sample progresses, the forcing moment will decrease proportionally. This design forces precise measurement of the loading moment. In addition, the removal of the belt transmission and the change in the method of fixing the sample will result in a higher reproducibility of the tests. The miniaturization of the device significantly reduced the costs of its construction, which will allow the construction of several identical machines and simultaneous testing of many samples.

5. Machine for multi-axis fatigue tests with a polyharmonic vibration generator

Another, interesting approach to the problem of building the device for testing complex load states was proposed by Garbacz and Macha from the Opole University of Technology (Fig. 9) [1,2].

The prototype of this device was a machine for inducing fatigue bending-torsional cycles from Amsler. The device diagram is shown in Figure 10.

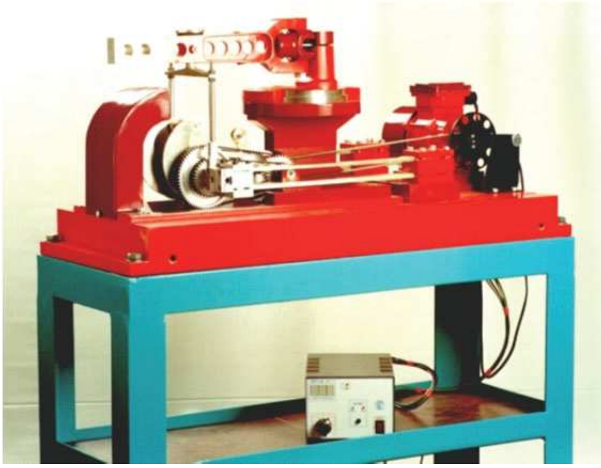

Fig. 9. Machine for multi-axis fatigue tests type MZGS-100PL/PZ

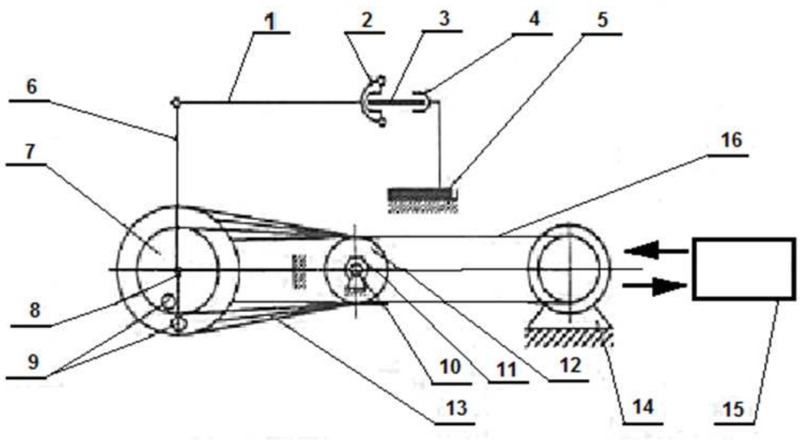

Fig. 10. Diagram of the MZGS-100PL / PZ device: 1 – lever, 2 – articulated holder, 3 – test sample, 4 – fixed holder, 5 – adjustable dial that sets the dependence of the torsion to the bending moment, 6 – articulated puller, 7 – polyharmonic vibrator, 8 – four flat springs, 9 – eccentric weights, 10 – intermediate shaft, 11 – bearing of the intermediate shaft, 12 – five pairs of gears, 13 – transmission of the drive with toothed belts, 14 – motor 15 – motor controller

The device was designed for testing small-sized samples – max 100 mm. The machine is built from an motor (14), whose speed is regulated by an inverter (15). The drive from the engine is transferred to a polyharmonic vibrator (7) with a toothed belt (16) on the intermediate shaft (10). Five gears with different diameters were installed on the intermediate shaft. One central and 4 output. On each of the four output wheels, toothed belts (13) are installed transferring the drive to one of the four wheels of the polyharmonic vibrator (7). The wheels of the polyharmonic vibrator are installed on the roller bearings of the vibrator shaft, the bearings of which are fixed to four flexible flat springs (8). The resulting variable force is transmitted through the articulated puller (6) to the lever (1), which is connected to the articulated sample holder. The joint assembly reduces forces to zero by stretching the sample, limiting the moments of forces only to twisting and bending in relation to the angle of the disk setting (5). The kinematics diagram of the drive is shown in Figure 11.

On each of the wheels of the polyharmonic vibrator, we attach weights one on each wheel. The rotation frequencies of the individual vibrator disks are as follows: f1 = f0 17 / 36 for the 1-st disk; f2 = f0 32 / 51 for the 2-rd disk; f3 = f0 32 / 60 for the 3-rd disk; f4 = f0 18 / 35 for the 4-th disk – the numbers of the vibrator disks correspond to the pairs of cooperating wheels (Fig. 12). By setting, before starting the machine, the implementation of the position of the vibrator polyharmonic wheels, we decide on the phase shift of the individual components of excitations on the shaft of the vibrator. Similarly, as in the devices presented above, there is a close dependence of the torsional and bending moment as a function of the twist angle of the disk (5), expressed by the formula:

$$tg\alpha = \frac{Ms(t)}{Mg(t)} \tag{6}$$

The sample load diagram is presented below (Fig. 12) [3,4].

The most important difference compared to the above-described machines is the polyharmonic oscillator, which allows the generation of very fast time-varying loads at a constant motor speed. The effect of this state of affairs is very interesting waveforms of modulated stresses (Fig. 13).

In each operating load spectrum, the dominant frequencies and the corresponding stress amplitudes can be distinguished. Such analysis leads to the presentation of the operational load as the sum of harmonic vibrations with different stress amplitudes and generally non-zero initial phases. It is also the basis for a simplifying assumption, in which the broadband frequency spectrum of operational load is approximated by a polyharmonic course with four component frequencies.

The most important advantage of the device is the possibility of obtaining very high vibration frequencies, which significantly shortens the time of testing. The device has been built and many tests have been carried out, confirming its durability and usefulness. Analysing the course of the bastard's characteristics, it is impossible not to notice the random character of the vibration course for one machine setting. It is difficult to talk about the repeatability of conditions for subsequent replicates of the tested samples.

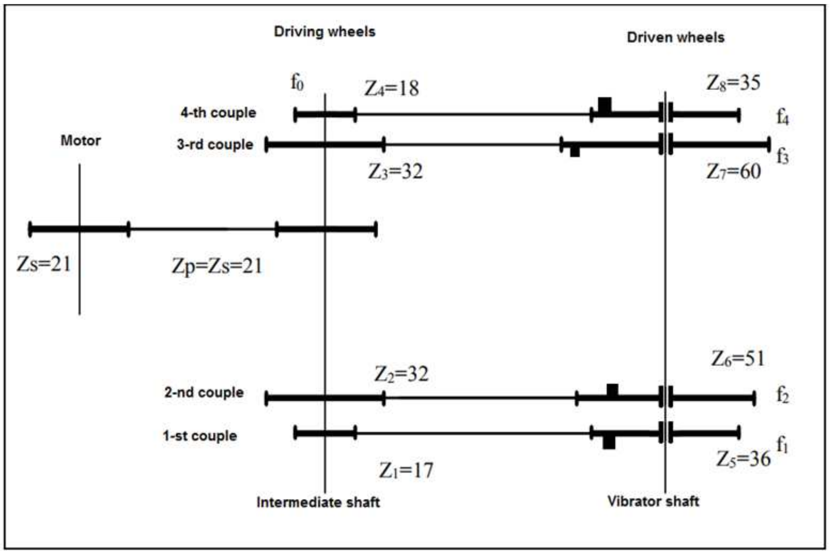

Fig. 11. The kinematics diagram of the polyharmonic vibrator drive of the MZGS−100PL/PZ machine

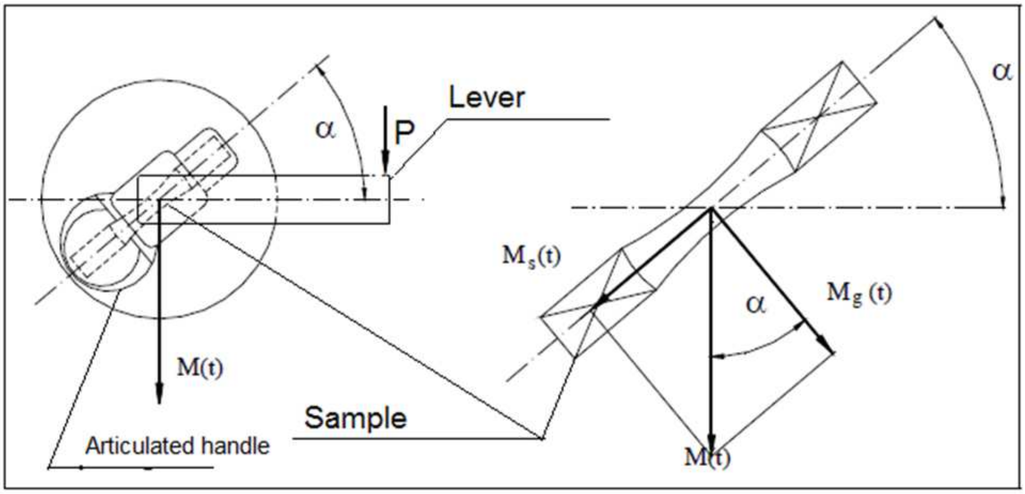

Fig. 12. Scheme of sample load as a function of angle P – extortion force, M(t) – resultant moment $M_s(t)$ – component of torsional moment, $M_g(t)$ – component of bending moment, α – angle of lever inclination

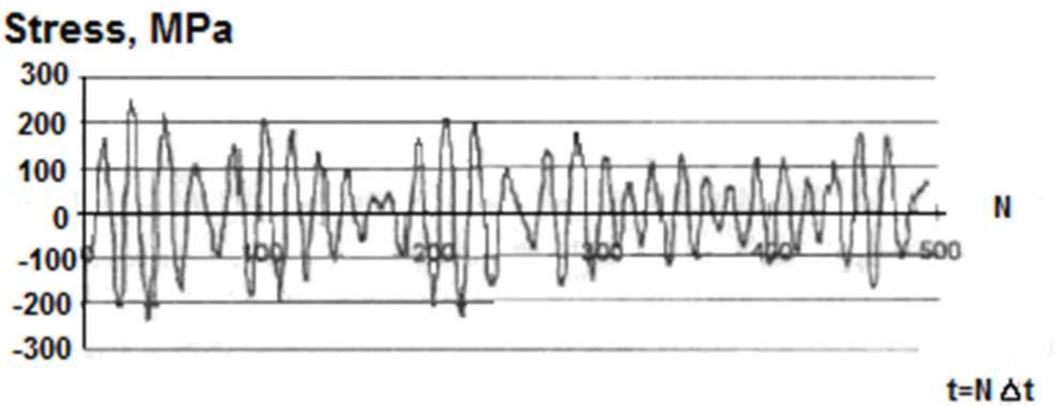

Fig. 13. An example of a real stress course determined experimentally on the basis of a signal from strain gauges placed on the machine's lever (sampling period Δt = 0.003 s)

The high and very high deformation frequency is not suitable for testing all types of materials. In the case of polymers and polymer composites, the high frequency of deformation causes changes in the strength parameters of the test sample. Polymeric materials at high deformation rates behave like fragile vitreous bodies with high stiffness, which are subject to destruction even with small deformations [3].

The common feature of the above-described machines and the described is the rigid, kinematic connection of the torsional moment with the bending moment (Fig. 14). The researcher is not able to change this relationship during the measurement. These devices do not allow simulation of the actual vibration characteristics occurring in the environment on the tested samples.

6. Hydraulic machine for multi-axis fatigue testing

At the Faculty of Mechanical Engineering at the University of Zielona Góra, a team led by Papacz, has attempted to build a device in which the torsional moment will not be related in any way to the bending moment. The conceptual design of such a machine is shown in Figure 15.

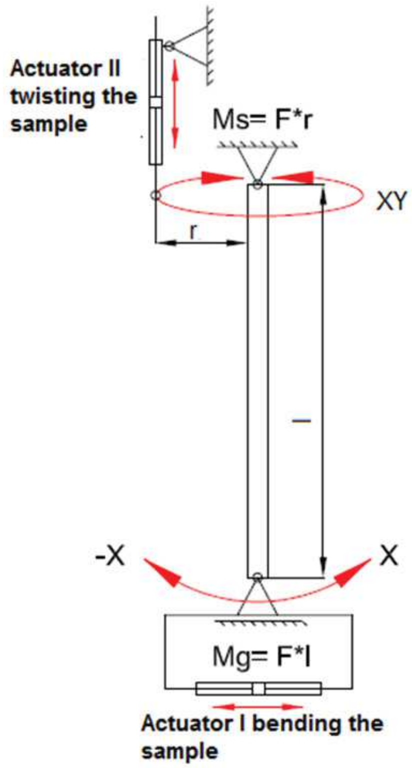

Fig. 14. Kinematical diagram of the KAT004: Ms – moment of twisting the sample, Mg – moment of bending the sample

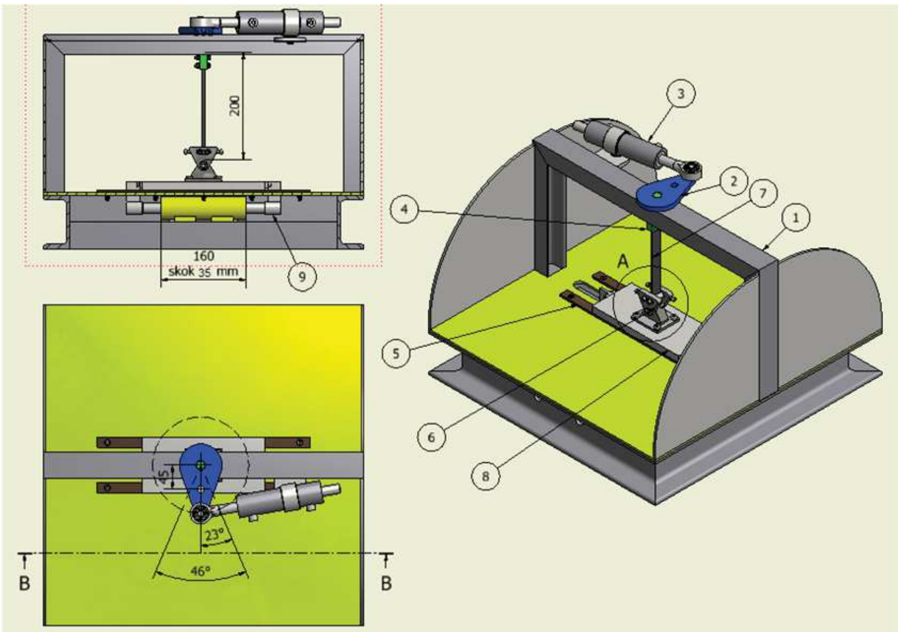

Fig. 15. Conceptual fatigue testing machine in a complex load condition: 1 – base with bearing frame, 2 – lever responsible for torsion of the specimen, 3 – bi-directional actuator responsible for torsion of the specimen, 4 – specimen sample, 5 – sliding list of the trolley, 6 – bottom articulated grip of the sample, 7 – tested sample, 8 – trolley, 9 – bidirectional lower cylinder responsible for bending the sample

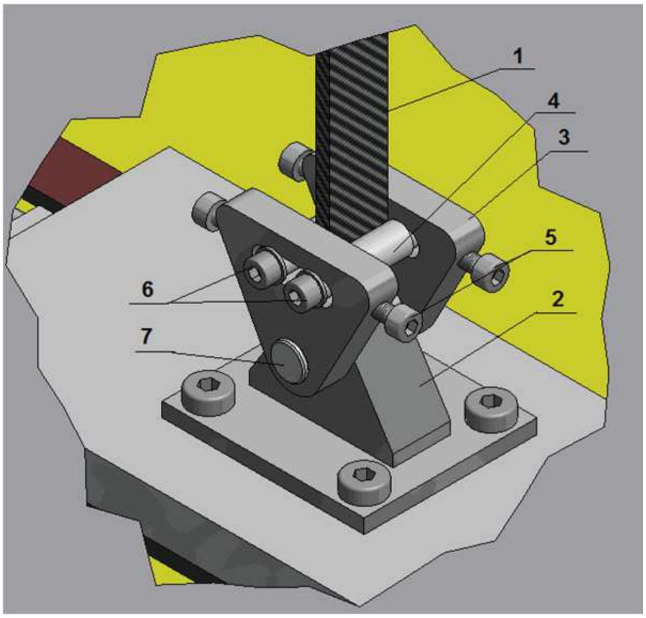

Fig. 16. Articulated holder: 1 – tested-sample, 2 – fixed base of the holder, 3 – movable upper part of the holder, 4 – movable rollers, 5 – screws adjusting the holder to the thickness of the sample, 6 – screws adjusting the width of the roller axis and screws adjusting the holder to the width of the tested sample, 7 – main axis of the holder

In order to eliminate the stretching of the sample during the movement of the wheel to the right and to the left, a special articulated mounting of the sample was designed (Fig. 16).

The designed holder construction allows the sample to slide freely as the trolley moves to the right and to the left on the rollers (4) equipped with self-lubricating slide bearings, and the joint (7) adjusts the angle of the holder proportionally to the sample extermination. This function causes that the breakthrough will not occur on the rollers of the holder.

The device is equipped with two double-sided cylinders with a pitch of ± 35 mm. This solution causes that, at constant pressure, the actuator operates with constant force regardless of the direction of operation. The upper cylinder cooperates with the lever and is responsible for twisting the samples. The maximum range of torsion angle depending on the position of the connection with the lever will enable twisting the sample in the maximum range of ± 23°. Both actuators have the same stroke of 35 mm in each direction. The built-in path sensor in the induction cylinders allows for the programming of successive amplitude sequences. Lower cylinder installed under the plate. Special actuator's ears are connected to the trolley on the right and left of it. The trolley with an adjustable articulated holder is secured against rotating around the axis of symmetry of the actuator through self-lubricating flat lists of sliding bearings.

The frequency of obtained vibrations in each of the planes can be set independently of each other and will depend on the range of the amplitudes set. With a vibration amplitude of 1 mm, the projected maximum vibration frequency will be above approx. 30 Hz.

The use of hydraulic drive in this type of devices generates problems related to the need to remove heat. The drive hydraulic system was designed in such a way that the oil heated by compression and work, flowing out of the engine cylinder do not return to the cylinder, but only to the tank of the hydraulic unit. Each actuator movement will be carried out with a new portion of oil. In a 90-liter tank, the thermal capacity of the system is so high that it can easily prevent overheating of the oil. In addition, the oil tank will be equipped with a copper coil allowing additional cooling with water if the system had to work at high ambient temperatures.

6.1. The advantages and disadvantages of the device

An unquestionable advantage of the device is the simplicity of the system and the possibility of any programming of moments and torsional amplitudes regardless of the moment and amplitudes bending the sample. The construction of the device allows for the reproduction of low-frequency characteristics from real machines or objects, enabling a comparative check of new materials with currently used ones. The disadvantage of the current design is undoubtedly the lack of vibration generation capabilities above 60 Hz, because this is the maximum frequency of switching of hydraulic distributors caused by the resistance and inertia of the slider system and oil flow in the hydraulic system.

7. Multi-axes fatigue testing machine from Shimadzu

The Japanese company SHIMADZU has many professional fatigue testing machines. Basically, it offers comprehensive testing systems from the device, through a sensor system to record and process data. In 2015, the Dynamic and Fatigue Testing Systems catalogue presented an interesting machine for multi-axis fatigue tests called XYZ 3-Axis Engine Mount Testing System [9] (Fig. 17).

The device is made of a base in the form of a cross (1) on which a fixed fixture fixing the sample (2) and two hydraulic cylinders in the X and Y axes (5,6) are installed. The Y axis actuator (7) is installed vertically on a special frame. The sample (3) is fixed on one side rigidly to the base (1) and the other to a special movable holder (4), which in turn is connected to a system of articulated tendons (8) with actuators (5,6,7). Actuators positioned in the X and Y axes enable twisting and bending the sample, while the vertical motor in the Y axis is responsible for its compression or stretching. Each of these processes can be carried out separately or simultaneously. The user decides on the sequence of switching steps of individual actuators, amplitudes and frequency of interactions on the sample.

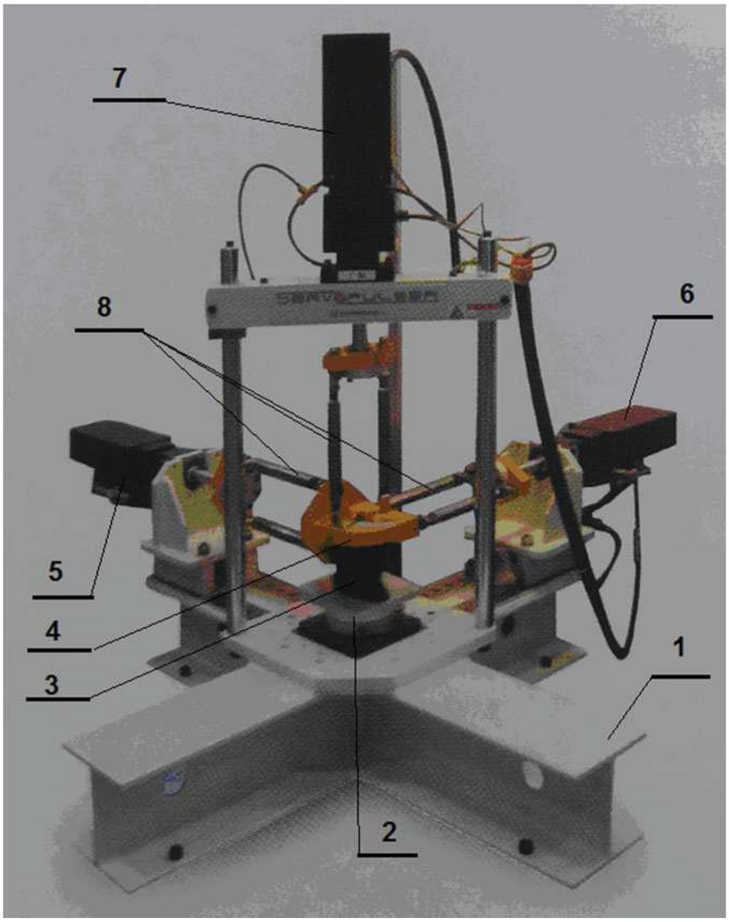

Fig. 17. XYZ 3-axes motors system: 1 – base with frame, 2 – sample holder, 3 – sample, 4 – moving sample holder with three degrees of freedom XYZ. 5 – displacement actuator in the X-axis, 6 – displacement actuator in the Y-axis, 7 – displacement actuator in the Z-axis. 8 – articulated joints in the Z-axis

The company does not disclose detailed technical data of the machine, claiming that it individually adapts it to the customer's requirements.

The advantage of the device is high technical progress of the machine delivered together with the control, processing and data registration system. The company's extensive experience and hundreds of similar produced devices guarantee the reliable operation of the device. The machine allows you to carry out tests in all axes, which makes it a very universal work tool for fatigue testing in a complex load condition. The disadvantage or even the barrier for many universities is the price of the device, which together with the system reaches several hundred thousand dollars. Despite such high costs, as in the KAT 004 device, it will not be possible to achieve high or ultra-high vibration frequencies.

8. Summary

The fatigue test program, both in terms of the type of loads and their size, should be planned in such a way as to reproduce the real working conditions of the tested structural elements with. This principle is of particular importance for constructions made of polymer composites. It should be remembered that polymer composites are materials specially designed for a specific application. The material, the type of reinforcement, the manner of its distribution and the amount of reinforcement measured in percentage by volume, are adapted to the directions of operation of the main loads. Also, polymer composites allow you to build parts and subassemblies of machines that integrate many functions in one element. They allow, for example, to generate various physico-chemical properties without a clear boundary between them in one element. This means that material data obtained from typical fatigue tests are of little use for the design of composite load-bearing structures. Typical devices for fatigue tests often do not allow to carry out the required type of loads. There is, therefore, a need to build devices to perform the required type of loads. The intention of the authors was to present various solutions of fatigue life test equipment allowing to implement the types of loads assumed by the constructors.

The article presents a review of fatigue testing devices for polymer composites in the assumed load condition. Physically existing devices as well as those in the design phase have been presented. Also presented are own concepts of the construction of such devices. The analysis of each device was completed with a description of its advantages and disadvantages. There are various constructor approaches to the problem of fatigue testing. The selection of a testing machine depends on the research program adopted.

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