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Application of Baushinger effect during prolonged storage in stressed state of elements of structures made of fiber reinforced plastic

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Abstract. The problem of the occurrence of irreversible residual deformations is reviewed arising in elements of structures made of carbon fiber reinforced plastic (CFRP) after removing the long and continuous load. These residual deformations impair accuracy of the space structures from CFRP after removing the long load. It is generally known that breaking of the material below the ultimate stress by load cycle reversal in the plastic region is called the Bauschinger effect. Design therefore usually precludes cyclic loading into the plastic region. However, in case of low-cycle loading, the Bauschinger effect can be applied for reduction of the residual deformations in such structures by the pre-loading with opposite sign. CFRP has two plastic deformation stages: the first is ruled by dislocation interactions with the fibers and a real the Bauschinger effect can be observed in repeated tension test. A second stage occurs after 0.6% total strain and is connected with a break of carbon fibers. Examples of the occurrence of residual strain in outer structures from CFRP are shown. A new way of long-term storage in a stressed state of structural elements from CFRP developed on the basis of the Bauschinger effect is presented. The possibility of realization of the proposed method of storage is also shown.

1. Introduction

Currently, there is a steady trend in the world towards the production of large-size space structures made of carbon fiber reinforced plastic (CFRP). At the same time, the forming elements of such structures in the transport (folded) position are often in a stress–strain. At the same time, during long-term storage of forming elements of structures from CFRP under load, residual deformations are observed after removal of the load. As a result, the geometric accuracy of the structure in the operating position is reduced [1, 2]. For example, in [3] provides evidence that during prolonged storage in a collapsed position flat graphite epoxy ribs appear elastic viscous strain which 7 days later after of deployment is recovered by 80%.

As another example of long-term storage of elastic-deformed elements of the design of antennas from CFRP, we can cite the elastically deployed reflector of the antenna, created by Boeing Satellite Systems (USA) (Figure 1a) [4]. After the deployment of the reflector, there were residual deformations which were taken into account as part of the total value of the standard deviation of the working surface from the theoretical [5, 6].

Also known is the design of the Russian folding antenna petal-type of space radio telescope "Radioastron" (Russia) (Figure 1b), forming elements of which are made of CFRP [7]. In this case, the period of time from the moment of placement of the folded antenna under the fairing of the launch vehicle in a horizontal position to the time of installation of the launch vehicle in a vertical position can be several weeks. During this period of time, the supports of the focal container of the folding antenna of carbon fiber are under the unilateral influence of its weight and the weight of the petals and the supports themselves. As a result, there may be residual elastic-viscous deformations, which must be taken into account as part of the total deviation of the antenna geometry from the theoretical value [1].

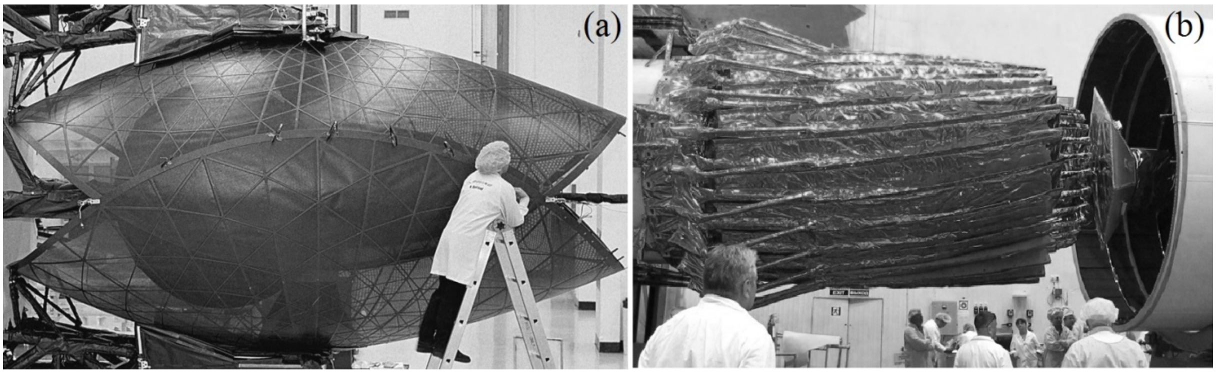

Figure 1. The elastically rolled reflector of the space antenna from CFRP (a) and the installation of the space radio telescope "Radioastron" with the folded antenna of petal type from CFRP inside the fairing of the launch vehicle (b).

Thus, the development of new methods aimed at reducing the values of elastic-viscous residual deformations that occur after the removal of long-term and continuous unidirectional load in the precision forming elements of structures from GFRP is an urgent task. And new method to reduce the value of residual deformations of structural elements from graphite-oxide CFRP after their long-term storage under unidirectional load is shown below [1, 2].

2. Description of prolonged storage method in stressed state of elements of structures made of CFRP

The method is based on one of the simplest glass blowing operations which is uniform rotation of the workpiece in the burner flame or in the furnace, providing uniform heating of the workpiece before its softening and preventing the shift of the mass and the influx of softened glass [8]. However, in real structural elements from VPKM to convert unidirectional load, for example from the action of gravity, in alternating by organizing their uniform rotation, as a rule, it is not possible or extremely difficult. Therefore, to solve this problem, the Baushinger effect was applied, which consists in reducing the limits of proportionality, elasticity and fluidity of materials as a result of changing the sign of loading, if the initial load caused the presence of plastic deformation [9, 10]. One of the reasons that prompted to apply the Baushinger effect to the solution of the above problem was that by the nature of the change in the deformation of the material in one cycle of alternating loading with a certain amplitude, in some cases it is possible to judge the pattern between the deformation during the first cycle and the number of cycles before failure [11], i.e. to predict the durability of materials in the area of low-cycle fatigue [12]. Currently, the Baushinger effect is found in almost all the studied crystalline bodies, including solid polymers, VPKM, as well as metal-carbon fiber composites with a polymer binder and is considered one of the features of the deformed state of materials [13-17].

Let us consider a simple example of the application of the Baushinger effect in the proposed method of reducing residual deformations in structural elements from CFRP after long-term storage under load [1, 2]. Figure 2a shows the evolution of the cantilever beam from the CFRP before and after its loading during storage without using the method considered here. In Figure 2b is the same, but using the specified storage method.

The proposed method of storage of elements of structures made of CFRP cracking under load, is that previously on samples-witnesses of the CFRP determine the magnitude of the Baushinger effect [10], then in the process of storage change the sign of the load on the opposite and the load values and also the duration of the two stages of storage is determined from ratios:

$$P_1 = P_2[\sigma_m/(\sigma_m - \sigma_e^{'})] \quad for \quad T_1 = T_2, \tag{1}$$

$$T_1 = T_2[\sigma_m/(\sigma_m - \sigma_e^{'})] \quad for \quad P_1 = P_2, \tag{2}$$

where P_1 and P_2 are the loads at the corresponding storage stages; T_1 and T_2 are durations of the corresponding storage stages; $\sigma_m/(\sigma_m - \sigma_e^{'})$ is the value of Baushinger effect; σ_m is the elastic limit of the reference specimen of CFRP; $\sigma_e^{'}$ is the elastic limit of the same witness sample when the load of the opposite sign is applied.

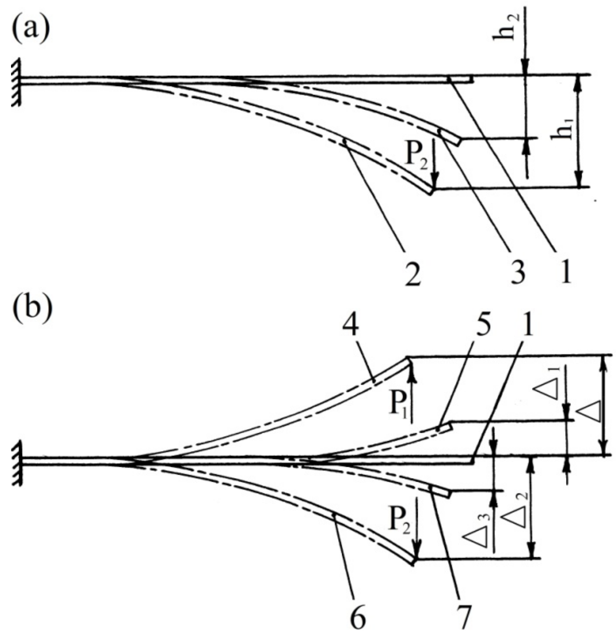

Figure 2. Evolution of the cantilever beam from CFRP before (a) and after (b) loading during storage.

Without the use of the proposed method, the beam from the CFRP to the application of the load during storage by the force P_2 occupies the position 1 (Figure 2a), under the load by the force P_2 - the position 2, while the beam is deformed by the value h_1, then after removing the load, the beam is restored for a time to the position 3 (the deflection is h_2). In the proposed method, the deflection value h_2 is lower (Figure 2b). For this purpose, the sample-witness beam of CFRP determine the elastic limit σ_m, then the specimen is subjected to loads of opposite sign, then re-define the limit of elasticity $\sigma_e^{'}$. Next, determine the magnitude of the Baushinger effect $\sigma_m/(\sigma_m - \sigma_e^{'})$. Before storage, an element from the CFRP, for example, the cantilever beam is loaded with a force P_1, determined from the ratio (1), the opposite sign than the load P_2 when stored for a time equal to the storage time. The beam is deformed by Δ (Figure 2b, position 4). Then, the cantilever beam is unloaded, and residual deformations Δ_1 (position 5) occur in it, directed in the opposite direction from the direction of the upcoming load during storage. Under the influence of the load during storage P_2 beam is deformed in the opposite direction by the value Δ_2 (position 6), and after removing the load is restored to the value Δ_3 (position 7), which is lower than without the use of the proposed storage method ($\Delta_3 < h_2$).

The proposed method can be applied for the case which is described in [5] as follows. Before storing the flat graphite epoxy rib under a load twisted around the hub for 7 days (T_2), it is twisted around the hub in the opposite direction and maintained for a time T_1, determined from the ratio (2).

Another example of the application of the method can be considered when the high-precision product from the CFRP, for example, the folding antenna from the CFRP has cantilever placement and the stressed state under the fairing of the launch vehicle (Figure 1, Figure 3). It should be noted that the cycle from the moment the product is placed under the fairing of the launch vehicle to its launch can be equal to several months, including the time of control checks carried out before the "rolling" of the fairing of the launch vehicle. In this example, the supports of the focal container from the CFRP are deformed by gravity and the irradiators "go" out of focus (Figure 3a). Since the product can be in such the cantilever position for up to several months, as the result of the creep of the polymer material, after the product is put into orbit in weightlessness, the irradiators will not return to the theoretical focus point [1], while the antenna characteristics will deteriorate.

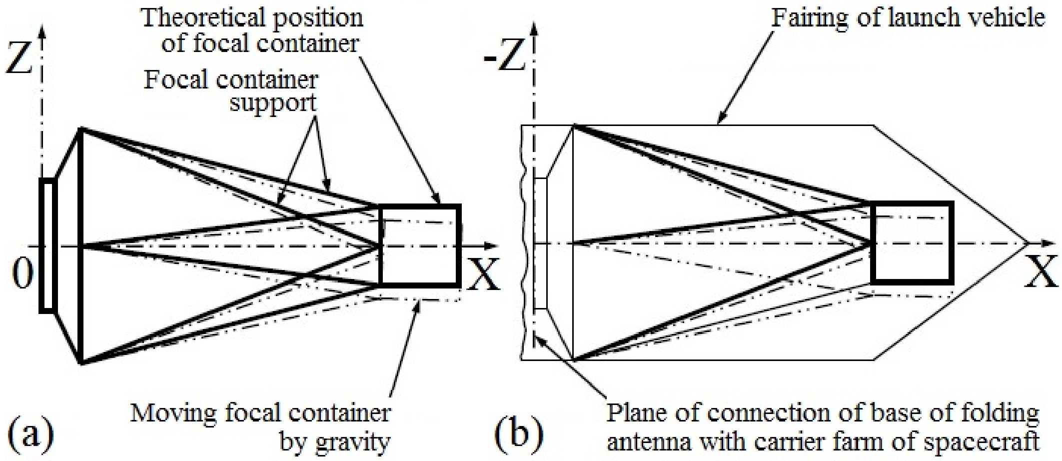

Figure 3. Gravity deformation of the focal container support of the folding antenna petal type to (a) and after (b) its placement under fairing of the launch vehicle (petals not shown).

To reduce the amount of irreversible residual deformations, it is possible to apply the proposed method. To do this, before placement of folding antenna under the fairing of the launch vehicle, its should be rotated $180°$ around the longitudinal axis X and in this position stand for the time T_1 (Figure 3b). While the time of the folding antenna under the fairing is equal to the time T_2. For example, if T_2 is 3 months and the value of the Baushinger effect is 0.95, $T_1= T_2\times0.95=3\times0.95=2.85$ months, i.e. during the control checks of the product, it will be rotated $180°$ around the longitudinal axis X relative to the position that the product will take under the fairing of the launch vehicle.

The real values of irreversible residual deformations the support system of the focal container were determined on its full-scale prototype (Figure 4). The support system is made in the form of the spatial parallel mechanism of the Stewart platform type [18], in which the spatial positioning of the focal container is carried out by an agreed change in the lengths of the rods [1, 19].

The rods of the support system are made of CFRP in the form of a tubular profile with an internal diameter of 32 mm, a wall thickness of 5 mm and a length of 4500 mm. The lower and upper endings of the rods through spherical bearings are pivotally connected to the tops of triangular steel base and platform.

Mechanical tests were carried out on the samples-witnesses of this tubular profile, made with different schemes of carbon fiber reinforcement. Figure 5 shows the calculated and experimental dependences of the longitudinal modulus of elasticity on the reinforcement angle. The observed differences are primarily due to insufficient efforts of the pressing of the prepreg, the tension of the longitudinal fibers uncontrolled bending and migration in the polymerization process, leading to a decrease of longitudinal modulus of elasticity under compression of the samples. The constructed dependences show a sharp decrease in the longitudinal modulus of elasticity with the deviation of the longitudinal fibers at an angle from 0 to 10 degrees relative to the axis 1 and more smoothly decrease is with the deviation of the longitudinal fibers at an angle from 10 to 30 degrees, as well as in the area from 60 to 90 degrees. The differences between the maximum and minimum calculated values of the elastic modulus are due to the technological imperfections of carbon fiber (fiber curvature, displacement, etc.).

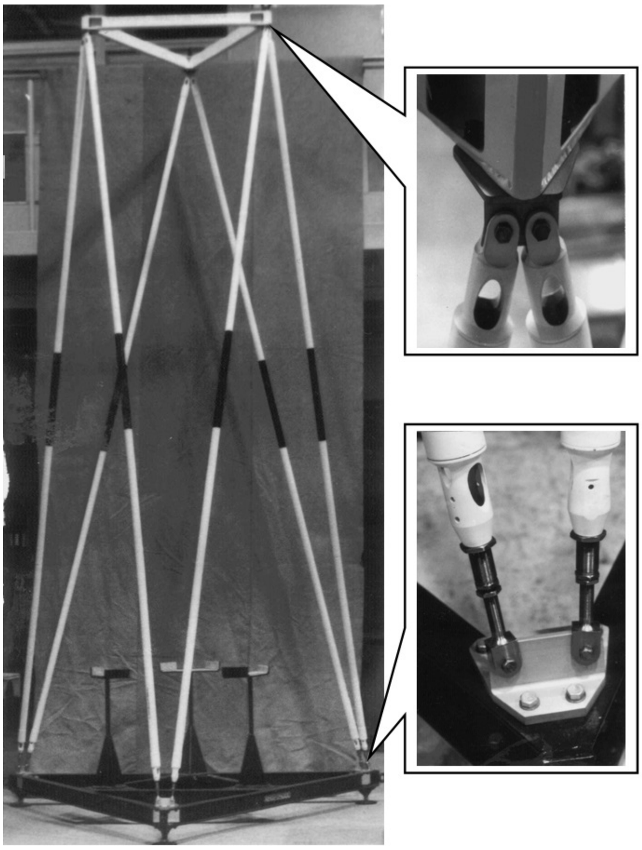

Figure 4. General view of the full-scale prototype of the support system of the focal container with alignment elements.

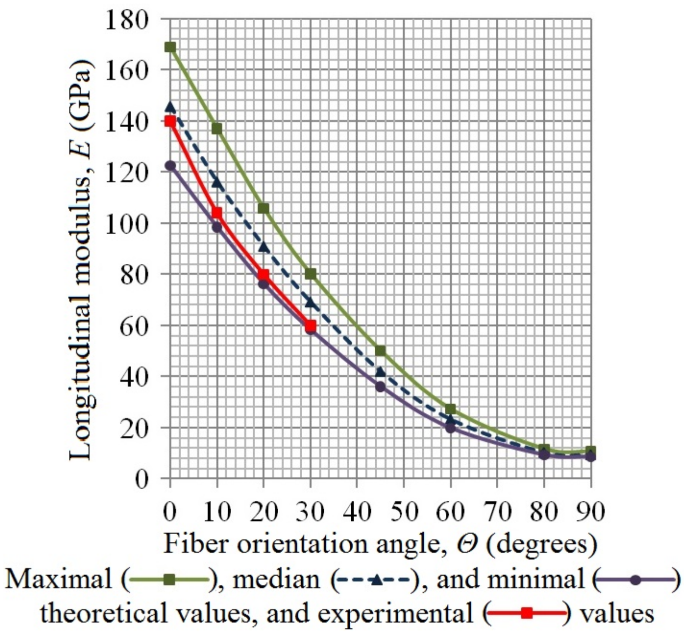

Figure 5. Longitudinal modulus dependences on the fiber orientation angle for maximal, median, and minimal theoretical values, and experimental values.

To obtain more accurate results, further tests were carried out directly on the full-scale prototype of the support system (Figure 6). At the same time, first the console part of the support system was counterbalanced by counterweights and the hour-type indicator was set to zero. Then the cantilever part of the supporting structure was loaded with force F equivalent to the gravity of the structural elements of the folding antenna which influence on the supporting system rods made of CFRP. Then exposure under load was carried out. At the same time, the holding time corresponded to the maximum value of the time spent by the loaded support system located in a horizontal cantilever position under the fairing of the launch vehicle (2.16×10^3hr.). Then the load was removed and the deflection corresponding to the residual deformation was measured. Then the time and *%* recovery of the spatial position of the support system relative to the initial position was determined, i.e. the value of irreversible residual deformation of the carbon fiber rods. However, this method of testing required long-term use of large production areas. In addition, the quality of the tests was influenced not only by the error from the loss of stability of the long tubular rod made of carbon fiber during its compression, but also by the error of the counterweights system itself. Therefore, mechanical tests of the full-scale prototype of the support system of the focal container were of a qualitative nature, in which the manifestation of the Baushinger effect in long tubular rods from the CFRP and the presence of irreversible residual deformations under prolonged exposure to static load were established. Further quantitative tests were carried out on the witness- samples cut off from the end sections of the tubular rods of the support system.

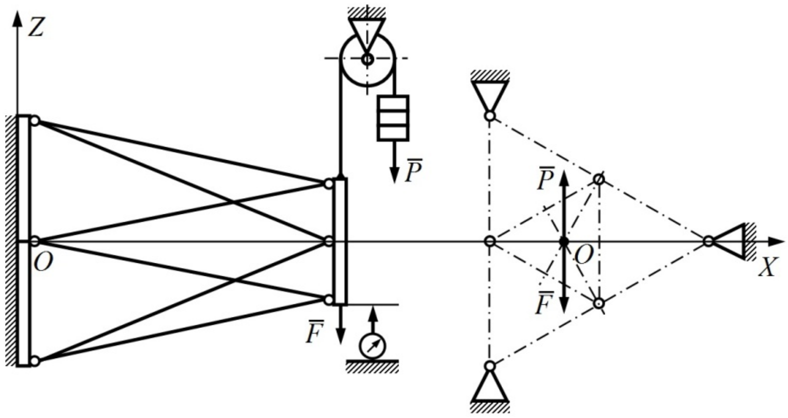

Figure 6. Scheme of testing of the full-scale prototype of support system of the focal container.

In part of the manifestation of the Baushinger effect in CFRP, the following should be noted. Composites based on carbon fibers are characterized by good resistance to long-term creep. Carbon fibers have a high modulus of elasticity and have a close to 1 ratio of yield strength to tensile strength along the fibers [20, 21]. For example, because of the creep under load along the fibers, which is *80%* of the original strength, the probability of failure after 105 hours is less than *10%.* In this case, the creep resistance of the carbon fiber applies only to the tensile load. However, if the direction of the load does not coincide with the direction of the fibers, then the physical and mechanical properties of the polymer matrix begin to play a role and it is necessary to evaluate the long-term strength of the material for laminates with fibers oriented in different directions.

During compression, part of the load is perceived by the polymer matrix and in unidirectional laminated plastic, so in this case there is also a creep phenomenon. Figure 7 shows the dependence of deformation on time due to creep during compression of unidirectional CFRP (prepreg brand AS/3501-6 manufactured by Hercules) under loads of 1025MPa along the fibers (dependence graph 1) and 190MPa in the transverse direction (dependence diagram 2) [21].

Thus, the dependence diagrams shown in Figure 5 and Figure 7 show the absence of the Baushinger effect in unidirectional fibers in the absence of technological imperfections of the composite. In the presence of technological imperfections in the range of fiber reinforcement angles from 0^0 to $\pm 80^0$, the Bauschinger effect will take place and its value will increase with increasing values of the reinforcement angle. At fiber reinforcement angles from $\pm 80^0$ to 90^0, the Baushinger effect will take place regardless of the degree of technological perfection of the composite.

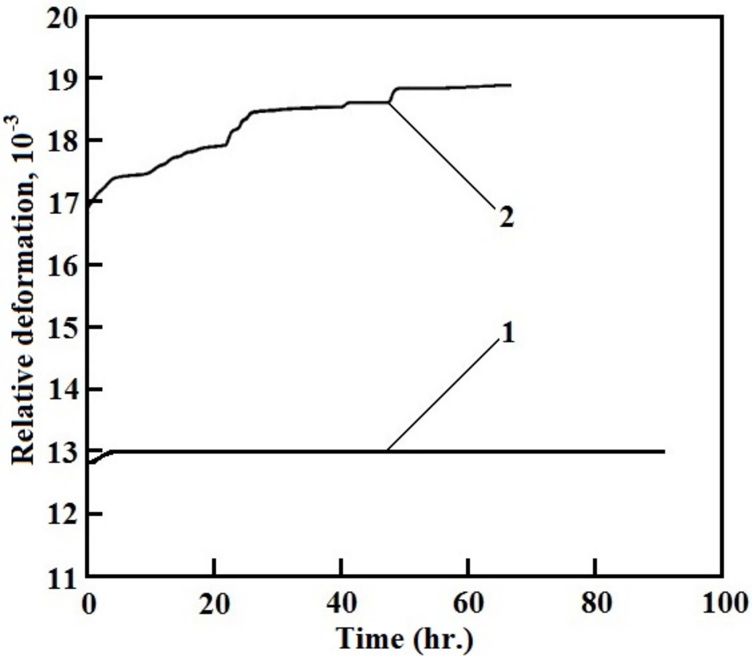

Figure 7. Dependences of deformation on time due to creep during compression of unidirectional CFRP under loads along the fibers (1) and in the transverse direction (2).

The manifestation of the Baushinger effect is also observed in other types of composite matrices with carbon fibers, for example, in layered composites based on an epoxy matrix and alternating layers of unidirectional carbon fibers and steel foil [16]. Also, the Baushinger effect was obtained during loading and unloading of a composite of short carbon fibers with a diameter of 7mkm and an average length of 100mkm (volume fraction of *30%*) randomly distributed in a metal matrix of pure aluminum *Al100* [15]. Tests of this material have shown that plasticity is manifested in two stages: the first is associated with the interaction between dislocations and fibers, and the second – with the rupture of fibers.

In cases where precision products from CFRP are stored for a long time in a container in a stressed state caused by gravity, the authors propose during the storage of the product to produce periodic turn of the container together with the product at 180°. In this case, the load on the product from gravity will change the sign to the opposite. Turn is to be performed using the time T1 from the moment of packaging the product in the container. For this case, the following General recommendations are developed:

- the number of overvoltages during storage should be minimal (because the strength at cyclic load is lower than at static);
- to obtain lower values of residual deformations after long-term storage, the storage conditions should be taken into account, i.e. the time T is equal to the time at which the product is stored in the same conditions (humidity, temperature, etc.) and, accordingly, overvoltage (change of the load sign to the opposite) must be made for each identical conditions separately, for

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example: $T^{'} = T_1^{'} + T_1^{'}$ - the time spent in the storage; $T^{''} = T_1^{''} + T_1^{''}$ - the time spent in the open area; $T^{'''} = T_1^{'''} + T_1^{'''}$ - time of the product under the fairing of the launch vehicle.

3. Conclusion
We have presented a new method of long-term storage in the stress state of precision structural elements from CFRP, developed on the basis of the Baushinger effect. The presented method will reduce the amount of irreversible residual deformations of products, manifested after the removal of long-term and continuous unidirectional load. This method is universal and can be used in various structures from the CFRP.

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