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STUDY OF RESIDUAL STRESS AND STRENGTH OF TRIPLEX GLASS

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Abstract- The article is devoted to the problem of determining the strength of triplex glasses, taking into account their technological and assembly residual stresses. An experimental and computational approach to solving the problem of determining the strength of triplex glasses, taking into account their technological and assembly residual stresses, is described, which is based on the use of two-exposure holographic interferometry in combination with chemical layer removal and the finite element method (FEM). The results of using the approach to analyze the strength of full-scale triplex windshields of a passenger car are presented. The results of using the approach to analyze the strength of full-scale triplex windshields of a passenger car are presented. The developed methodology for determining residual stresses and permissible deviations in the geometry of the triplex glass of a car windshield can be generalized to improve the technology of manufacturing windshields of watercraft, aircraft and other modern equipment.

Keywords: Triplex Glass, Residual Stresses, Holographic Interferometry, Chemical Layer Removal, Finite Element Method, Real Glass Strength.

1. INTRODUCTION

When creating modern cars, aircraft, ships and other high-speed vehicles, triplex glass is widely used - structures that consist of two layers of glass of the same shape, connected by a transparent adhesive layer. The need to use a layered structure is dictated by the requirement of safe operation while maintaining good light transmission of the glass. Triplex glass is increasingly being assigned functions of load-bearing elements, so issues of reliably ensuring their strength properties are of great importance.

The existing technologies for the production of such glasses are still far from perfect. One of the ways to make them is as follows. A blank is cut from a flat sheet of glass, its edges are machined, during which, as a rule, microcracks and other defects appear in them, significantly reducing the initial strength of the glass. Next, the workpiece in a special unit is heated to a plastic state, takes the necessary shape under the action of its own weight and cools down slowly. The resulting blanks of the required curvature are connected in pairs in a mold under normal pressure or vacuum by means of an adhesive film.

This technology is accompanied by a significant variation in the deformation and strength properties of finished products. Sometimes the load-bearing capacity of triplex glasses decreases so much that their spontaneous cracking occurs during storage and transportation under normal conditions. Spontaneous cracking of windshields indicates the presence of large technological residual stresses in them, which are mainly due to the uneven cooling and high sensitivity of the glasses to temperature fluctuations, and technological factors of their manufacture.

In addition, stresses often remain in the glass after its installation, due to differences in the geometry of the contour of the glass and the opening into which it is installed. That is, in addition, there are also mounting (assembly) residual stresses that are superimposed on technological stresses. At the same time, the field of total residual stresses of triplex glass turns out to be quite complex, and its bearing capacity and fracture parameters are difficult to predict. Thus, the wider use of triplex glasses is associated with the problem of identifying their residual stresses and correctly taking into account the latter in the calculations of the strength characteristics of the glass. The uncertainty of the nature of the distribution of residual stresses over the thickness and area of the triplex, the amorphousness and fragility of the glasses not only significantly complicate the theoretical analysis of its real strength, but also prevent the use of most mechanical and physical methods of controlling these stresses in solving the problem [1-3].

In recent years, laser interference-optical methods (holographic interferometry and electronic speckle interferometry) have been increasingly used in the research and diagnosis of residual stresses of structural elements and assemblies [4-9, 11-14]. As a rule, to release stresses and calculate their thickness distribution, these methods are used in combination with the methods of holes, grooves, FEM, etc. [10, 15, 16]. The authors are not aware of the work on the use of interference-optical methods in the diagnosis of residual stresses, strength and fracture of triplex glasses. To solve the problem under consideration, a specially developed experimental and computational approach is used, combining advantages of holographic interferometry, method of chemical layer removal and methods of finite element analysis.

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2. HOLOGRAPHIC DETERMINATION OF TECHNOLOGICAL RESIDUAL STRESSES IN GLASS

Full-scale triplex windshields of the VAZ-2109 (VAZ-2108) car were used in the research. Statistical data on the destruction of such glasses during their installation and start of operation are presented by the developer of avtoviya [13]. Analysis of statistical data shows that in most cases a crack occurs in the upper corner zones of the product on its edge (Figure 1). At the same time, of the 66 analyzed data of the collapsed glasses, the crack began in the inner layer of 48 samples (on the left - 28, on the right- 20), in the outer layer of 18 (on the left- 8, on the right- 10).

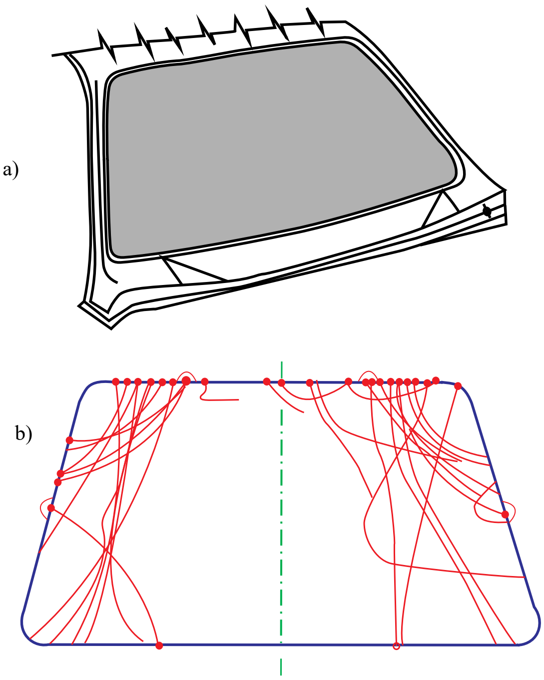
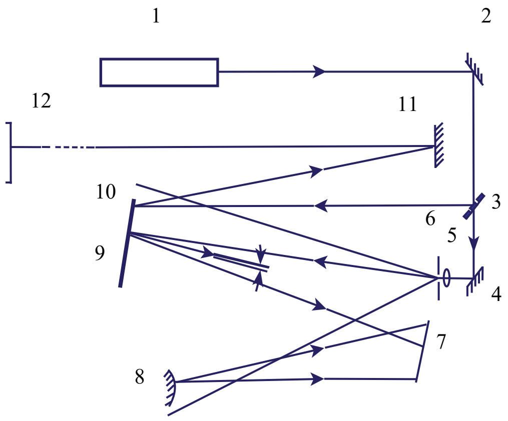


Figure 1. General view of the triplex windshield in the car window, a) statistical data on the localization of its cracks, b) at the stages of installation and start of operation (view from the salon)

To study the distribution of technological residual stresses over the thickness and area of the glass, samples cut from various zones of windscreens with dimensions of 0.15×0.15 m were used. 6 samples (1 series) were prepared from the central zone (Figure 1), 9 from the corner zones (2 series). Before the experiment, the observed side of the sample was painted with white paint, followed by the application of a coordinate grid. In the experiments, a single-hologram optical scheme with a weakly divergent object beam was used [10] (Figure 2). The sensitivity of the circuit to the deflection of the sample was close to the maximum and changed slightly within the observed surface (the ψ angle between the sensitivity vector of the circuit and the direction of the vector of normal movements of the sample was limited to the range of -4.5° ... +4.5°).

The desired stresses were determined by the method of two-exposure holographic interferometry in combination with chemical removal of layers. To fix the sample on the working plate of the holographic installation and return it to its original place after processing with the necessary accuracy, the author manufactured a special device consisting of a plate with three ball bearings, which was rigidly fixed on the desktop of the holographic installation, and a removable part with three corresponding slots for fixing the sample.



1- laser; 2,4,10,11- flat mirrors; 3- translucent mirror; 5- lens; 6- diaphragm; 7- photographic plate, 8- spherical mirror; 9- triplex sample, 12- remote screen

Figure 2. Optical scheme of the experimental installation

The sample fixed in the device was placed on a holographic installation, exposed, removed from the installation and etched with a special solution of fluoric acid with the addition of sulfuric acid and water. The solution was applied with a brush to the entire back of the test sample and mixed evenly with the addition of new portions for 30 minutes, which ensured uniform etching of the sample to a depth of $(20…24)\times10^{-6}$ m. Then the remains of the solution were carefully removed, the sample returned to its original position, held for 1 hour and exposed a second time. Thus, an interferogram of the deflection field of the sample was obtained, due to its transition to a new equilibrium state after the release of residual stresses in the etched layer. Similarly, patterns of interference fringes of the sample were consistently obtained during its further layer-by-layer etching up to 70-75% of the thickness of the carrier layer, first on one side, then on the other; characteristic of them are shown in Figure 3a and Figure 3c. The decoding of interferograms was performed according to the formula [7].

$$L = \frac{\lambda}{2} \times \frac{N}{\cos\theta \times \cos\psi} \tag{1}$$

To control the direction of deflection of the sample, a small mirror 10 was attached to the most mobile part of it, reflecting a laser beam onto a remote screen (Figure 2). The deflection sign was determined by the direction of deflection of the light spot on the screen between two exposures. Typical deflection distributions of samples along their longitudinal coordinates are shown in Figures 3 and 4. Based on the deflection values found, the longitudinal σ_{rt} normal residual stresses in the central zone of the sample at various levels from the surface were calculated. The calculation was performed according to the Equation (1) of I.A. Birger [2]:

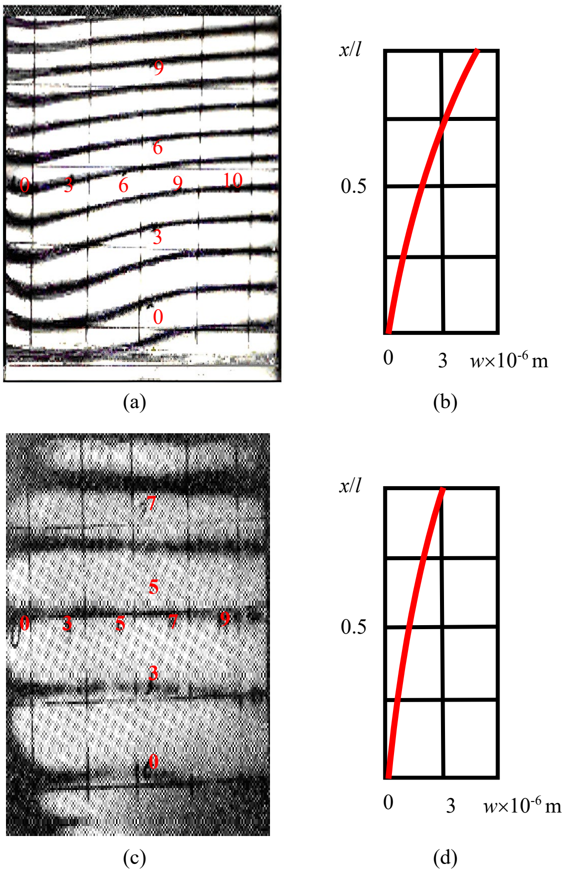


Figure 3. Characteristic interference patterns of the triplex sample and the corresponding distributions of its deflections along the central vertical axis after removal 2nd (a, b) and 30th (c, d) layers

$$\sigma_{rt} = \frac{E}{2\ell^2}[(2H-h_i)^2 \frac{df}{dh_i}(h_i) - -4(2H-h_i) f(h_i) + 2\int_0^{h_i} f(h)\,dh] \quad (2)$$

The results of experiments with cut samples (Figure 4), due to the self-balance of residual stresses and the validity of the Saint-Venant principle, were generalized to solid triplex glasses (Figure 5). Regarding the distribution σ_{rt} of glass thickness and area, the following was obtained (2). Technological residual stresses in the tested windshields are non-uniform in area and thickness. On the convex sides of the load-bearing layers they are compressive, on the concave sides they are tensile. In the central zone of the glasses (for samples of series 1), the largest residual stresses in absolute value are relatively small (10±5) MPa.

In the corner zones (for samples of series 2), the stresses reach (45±10) MPa values, which is equal (57±13) % to the tensile strength of the tested glasses. This fact explains the high percentage of cases of the beginning of the destruction of these glasses during storage and transportation. With such values of technological residual stresses, random combinations of even not very large loads can lead to total stresses that exhaust the bearing capacity of the windshield in angular zones.

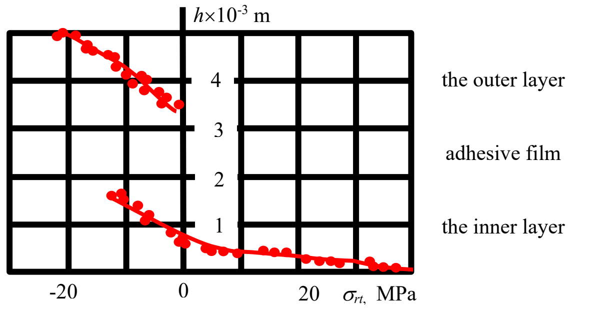
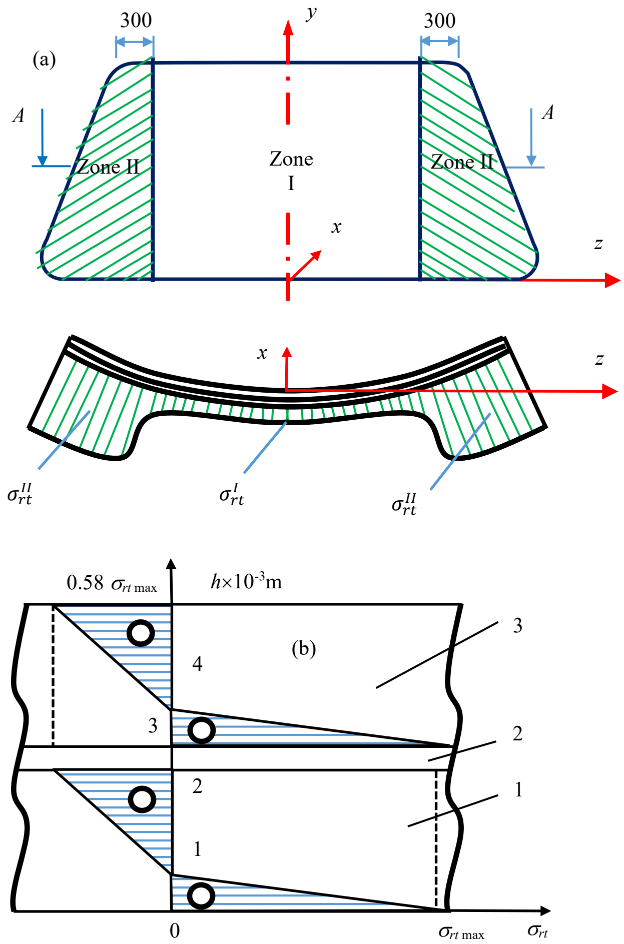


Figure 4. Distribution of technological residual stresses in the sample of the 2nd series by thickness (dots indicate the results of calculations based on interferograms, curves indicate their average values)



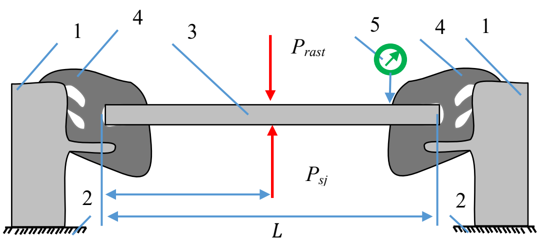
1,3- inner and outer layers of glass; 2- film

Figure 5. Generalized linearized diagrams of the distribution of technological residual stresses over the area (a) and thickness (b) of the windscreen (in the zone I $\sigma^{I}_{rt\,max} = +10$ MPa ; in the zone II $\sigma^{II}_{rt\,max} = +45$ MPa)

As the layers are removed, the absolute values of residual stresses decrease. At the level of $h \approx (0.25...0.30)\,H$, they become close to zero, then, changing the sign, they increase. The results obtained make it possible to take into account technological residual stresses when calculating the stress-strain state (SSS) and the bearing capacity of the triplex windshields under study.

3. FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES OF GLASS AND AN ASSESSMENT OF ITS REAL STRENGTH

To calculate the assembly residual stresses and the actual strength of the glass after its installation in the opening of the car body, it is necessary, in addition to the deformation and strength properties of the triplex, to have data on the deformation of the seal and the body opening, as well as characteristic deviations of the geometric dimensions of the glass and the opening from the nominal (ideal) parameters. Due to the lack of data on the deformation characteristics of the body opening, the latter was supposed to be absolutely rigid, which obviously goes into the margin of safety and resource of the windshield. The deformation properties of the seal were determined by a specially performed experiment according to the scheme shown in Figure 6.



1- Simulator of the profile of the opening of the windscreen; 2- Desktop; 3- Rigid steel plate; 4- Seal fragment; 5- An hour-type indicator with a division price 01×10^{-3} m

Figure 6. The scheme of the device for determining the deformation properties of the windshield seal

Two identical fragments of the seal with a length of 0.06 m were sequentially loaded in the transverse direction for tension (from the cabin) and compression (into the cabin), the displacement of plate 3 was recorded using an indicator. The obtained dependence of the seal deformation on the magnitude and sign of the linear force is shown in Figure 7. We see that the dependence is close to linear in compression and significantly nonlinear in tension.

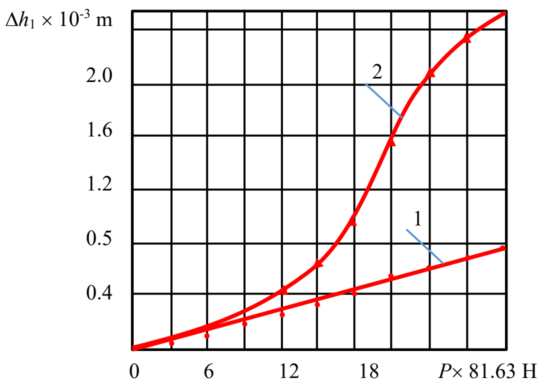


Figure 7. Dependence of the short–term transverse deformation (displacement) of the seal on the linear load (1- compression; 2- stretching)

For triplex glasses of the same series, the results of measurements of the deviation of the glass geometry from the nominal value presented by the developer were considered. Two typical cases of deviations were analyzed: "propellability" and the general case (Figure 8). In both cases, the geometric parameters of the glass edge were inconsistent with the nominal value only in the direction from the plane (on the *x*-axis). The dependence of the deviations along each edge of the glass was assumed to be linear.

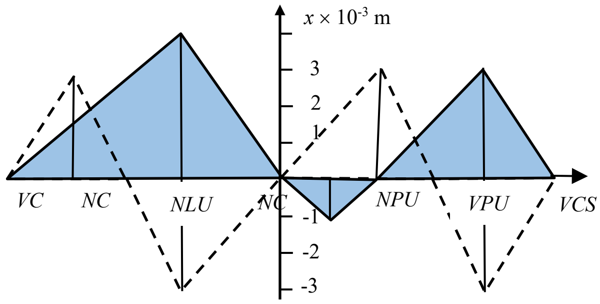


Figure 8. Typical distributions of deviations of the windscreen contour from the nominal value with its "propeller" (dashed line) and in general (solid line) VC, NC - centers of the upper (B) and lower (H) edges of the glass; NLU, NPU and VLU, VPU - lower (H) and upper (C), left (L) and right (N) corner points of the glass

In finite element calculations, a specially developed software package was used, which has a number of features related to the specifics of the calculated object. In particular, the scheme of dividing the object of study into three-layer finite element packages with three elements in thickness and thickening of the grid near the short sides of the glass was used. A parametric three-dimensional finite element was used. This made it possible to take into account the curvature of the glass surface with a relatively small number of elements into which the structure is divided. The element was anisotropic, which made it possible to take into account the heterogeneity of the mechanical properties of the triplex, associated with its layered structure, and the three-dimensionality of the SSS of glass, especially in the area of its attachment.

The linearized distribution of experimentally found technological residual stresses was considered as a load (Figure 5). In addition, stresses in the glass are caused by displacements set at the edges, which characterize the discrepancy between the true shapes of the glass and the opening, taking into account the elasticity of the windshield seal. The deformation of the seal is used to build an iterative process that allows you to determine the actual conditions on the edges of the glass during assembly. At each step of the iterative process, the displacements occurring at the boundary nodes and the actual deviations of the edges of the glass give nodal forces determined using the dependence presented in Figure 8.

For these cases of glass surface deviations, assembly residual stresses σ_{rc} were calculated in the form of projections onto coordinate axes, total residual stresses $\sigma_{rr} = \sigma_{rt} + \sigma_{rc}$ and their intensity σ_i , as well δ as permissible (safe) deviation values. The distributions of total stresses along the edge (the weakest part) of the glass are shown in Figure 9.

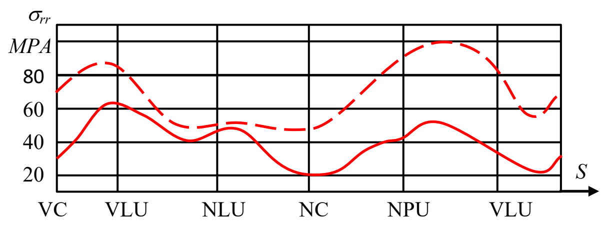


Figure 9. Distribution of total tensile residual stresses along the contour of the inner bearing layer of the windshield with typical deviations of the shape of its surface from the nominal value (according to Figure 8)

The field of permissible geometry deviations was determined by trial calculations using the strength criterion $\sigma_{i\max} \leq [\sigma]$. Here $\sigma_{i\max}$ is the maximum intensity of the total stresses on the edges of the glass; $[\sigma]$=76.92 MPa is the tensile strength of triplex, experimentally determined as the tensile strength of the glass used in it, taking into account the nature of the processing of its edges. When analyzing the results obtained, the following was noted. The maximum modulus assembly stresses σ_{rc} (σ_y or σ_z), as expected, are localized at the edges of the glass. The most dangerous stresses for glass are tensile stresses, so we will analyze only these stresses further.

In the first case of the distribution of deviations ("propeller"), the maximum values of assembly stresses are obtained in the peripheral zones of the glass, where in the outer load-bearing layer they reach values of 23...30 MPa. In the inner load-bearing layer, the stress is significantly higher - from 54 MPa to 75 MPa. That is, in the peripheral side zones of the glass, including the upper corners, the assembly stresses are close to the tensile strength of this triplex (76.9 MPa). Minimum assembly stresses (2...9 MPa) are localized mainly in the central sections of the upper and lower edges of the windshield in both the outer and inner layers. (Recall that the calculations were performed for an absolutely rigid body, and taking into account its real rigidity will reduce the level of these stresses).

Total voltages $\sigma_{rr} = \sigma_{rt} + \sigma_{rc}$ ($\sigma_y + \sigma_{rt}$, $\sigma_z + \sigma_{rt}$) in the outer layer of glass reach values of 22...30 MPa. In the inner layer at the sides and in the upper corner zones, the total stresses exceed the tensile strength of the glass, and significantly (up to 87...105 MPa) (Figure 10). The minimum total stresses are localized in the outer layer and amount to ~0.5 MPa. At the same time, equivalent stresses exceed the tensile strength over almost the entire surface of the windshield and reach values of 90...107 MPa, which is (17-39) % more than the tensile strength. Consequently, in this case, the safe deviations of the glass surface from the nominal value should be significantly smaller.

From the resulting distribution of calculated permissible surface deviations from the nominal value it follows that the maximum deviation in the case of the considered "propeller" should not exceed 2.58×10^{-3} m, provided that the body opening is absolutely rigid. Obviously, the magnitude of this deviation will increase with a decrease in the bending rigidity of the body in the area of the opening.

In the second (general) case of distribution of deviations, assembly stresses reach maximum values in the internal load-bearing layer of glass along the left edge and in the upper left corner (50...58 MPa), as well as along the right edge and in the upper right corner (49...67 MPa). Minimum stresses (4...7 MPa) are noted in this layer in the left halves of the upper and lower edges of the glass, as well as in the outer load-bearing layer in the right halves of the upper and lower edges. The highest total stresses reach values of 60...63 MPa in the outer layer of triplex at the right side. The same magnitude of total stresses in the inner layer arise in the corner zones of the other side (Figure 9). The calculation showed that in this case the maximum deviation of the windshield surface should not exceed 4.0×10^{-3} m.

It should be noted that in the considered cases of geometry deviations, the contribution of process stresses to the overall picture of the residual stress state after assembly is of the same order as the contribution of assembly stresses. Large stresses in the windshield appear where technological and assembly residual stresses are summed up. And although each of them does not exceed the strength limit of triplex, their sum turns out to be greater than this limit, especially with the "propeller" glass. Comparing the distribution of tensile total residual stresses along the edge of the glass (Figure 9) with the localization of cracks in such glasses at the stages of installation and the beginning of operation (Figure 1, right), we see that the cracks originated precisely in the zones of maximum total stresses.

4. CONCLUSION

Thus, studies have shown good effectiveness of using the presented approach in diagnosing the strength properties of triplex windshields. The approach makes it possible to obtain reliable and fairly accurate data on their load-bearing capacity, taking into account residual stresses, as well as to make scientifically based adjustments to existing tolerances for deviations of the glass shape from the nominal value. The results obtained were used at AvtoVAZ to solve the problems of reducing the breakage of triplex windshields of VAZ-2109 and VAZ 2108 cars at the stages of their transportation, installation and start of operation. The developed experimental and computational approach, methods for determining residual stresses and permissible deviations in the geometry of triplex glass can be used in the design and improvement of laminated glass manufacturing technology.

NOMENCLATURES

Symbols / Parameters

L : The magnitude of the displacement vector (deflection)
λ : Wavelength of the laser radiation used
N: The order of the interference fringe at a given point
θ : Half the angle between the directions of illumination and observation of the point

ψ : Angle between the vector $\overline{L}$ and the sensitivity vector of the optical circuit (bisector of angle 2θ) at a point

$E = 68.25\times10^{9}$ Pa: The modulus of elasticity of auto glass (determined experimentally in this work)

$\ell = 0.135$ m: Length of the cantilever part of the sample

h_i: Distance from its surface to the i-th etched layer

$H = 2.24\times10^{-3}$ m: Initial thickness of one load-bearing layer of triplex

$f(h) = \sum_i w_i$: Maximum deflection caused by successive removal of layers dh to this level

$df(h_i)/dh$: Derivative of the maximum deflection function for a given level h_i

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