DETERMINING THE DEGREE OF STRENGTH LOSS AND ASESSMENT OF THE POSSIBILITY OF FAILURE OF SHIP HULL STRUCTURES OF COMPOSITES IN THE ZONE OF DELAMINATION

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ABSTRACT

The report discusses the principles of accounting changes in the mechanical characteristics of the ship hull structures made of composites in the zone of delamination defect. The entire surface of the hull plating of composite is regarded as a system of plates, cylindrical, conical and spherical shells; there is a method for calculating the strength for each of them. Changing the mechanical properties of plate or shell in the delamination zone is taken into account through a change in the element cylindrical stiffness. Changing the mechanical properties associated with the composite aging is taken into account by reducing the values of Young's modulus and Poisson's ratio according to the procedure laid down in the Rules of the Russian River Register. The probability of uncontrolled delamination defect growth is accounted for by calculating the critical stress in the defect area and comparing the calculated value with the limit one. The numerical computation of allowable stresses is performed.

INTRODUCTION

In accordance with the practice prevailing in the global shipping industry, one of the reliable criteria for assessing the technical condition of the ship hull is the identification and registration of existing therein various operating defects and wear. The development of operational defects in the hull structure leads to reduction of its strength properties as well as the ability to withstand adverse operational effects. Upon reaching a certain size of the defect or wear, stresses acting in the construction in the area of its location, exceed the ultimate stress, established by the designer and the manufacturer of the vessel, as the maximum permissible. This can lead to both a structural failure at design regimes of motion and a disproportional increase of the zone of accidental failure in abnormal operating conditions. Such hulls are considered to have limited seaworthiness, and later on – to be unfit for use. Unlike other materials used to manufacture ship hulls, layered composites such as fiberglass in the process of aging practically do not change their appearance and size, but internal defects such as delamination appear in them.

Classification societies, as well as other navigation participants, performing technical monitoring and supervision of vessels made of composite materials in the course of their operation, need a reliable estimate of the technical condition of these vessel hulls. For example, in accordance with the Rules of the Russian River Register, the technical condition of the plastic hull is recognized as unfit in cases of shell delamination and bond from the shell and elements of the framing, as well as the crack appearance on the shell and framing. At the same time, nondestructive testing hulls of composites at the age of five years and more reveals on average, up to 200-300 areas containing inner defects such as delamination of different sizes (Fig. 1) [4]. Assessment of changes in the strength and stiffness of the whole plastic hull or its individual elements, in the case of above mentioned defect appearing, is not provided by the Rules of the Russian Waterway Register. Thus, the interpretation of the results of inspection of the hull made of composite materials, in order to assess its strength and durability, is an urgent task.

The complex of studies examining different aspects of the mechanics of composite materials, including those containing various internal defects such as cracks and delamination has been carried out to date by Russian scientists. The works of such scholars as V.V. Bolotin, L.A. Bohoeva, G.P. Cherepanov and a number of others must be mentioned here. A number of works is devoted to the analysis, valuation and assessment of operational loads and durability characteristics of ship hulls of composite materials, a way of assessing the technical state of the hulls in operation, a description of the operational behavior of individual elements of the gliding vessel hull made of composite materials under hydrodynamic loads There are works containing calculation methods for assessing the mechanical properties of the composite in the area of the delamination defect. The assessment was made by various numerical methods, first of all, by the finite element method (FEM).

Application of the calculations using the finite element method for evaluating the strength of the elements of the hull of composites being in operation and having a large number of delaminated sections is technically and economically very costly. It is necessary to have a simpler and more affordable way of determination the extent of the strength loss for the ship hull made of composite in the area of internal defects such as delamination of operational nature and assessment of the possibility of its failure.

PROBLEM STATEMENT

G.P. Cherepanov considered in detail the laminating cracks development, leading to failure of the composite structure element (Fig. 2) [5]. He also described the mechanisms of its development. According to the latest research in the field of composite materials failure, the tension of layered composites causes at first longitudinal cracking of the composite, starting with the matrix, which initiates the destruction of fibers. The longitudinal crack extends not strictly along them, but cuts a part of them. The formed surface plays a part of a defect. Groups of cut fibers can delaminate, resulting in a secondary longitudinal crack, and new cut fibers appeared. As a consequence, there is an avalanche material spillage into small fragments.

It is believed that delamination is developing when the tensile stress σ reaches the threshold value σ_c. In this case the initial crack makes 90^0 turn and begins to grow along the fibers. Thus, there is competition of two processes - the crack growth across and along the fibers. When considering the problem of cracking in the case of fiber composite tension near the initial imperfection in the form of a hole, the critical stress σ_c. is calculated by the Griffith's criterion, wherein the size of the hole diameter is considered to be the limit size of the defect [1].

A method for calculating the strength of ship hull structure elements of composite materials containing internal defects such as delamination is proposed for determining its technical condition in the following sequence:

- the external loads acting on an element of the ship hull structure of composites containing the internal defects such as delamination are defined at normal operation according to OST5.1068-75 "Hulls and Hull Structures Made of Fiberglass. Strength Calculation";
- the design schemes of a ship hull structure element of the composites at the place of the detected defect are determined for the entire structure and for the same structure containing a defect;
- the design parameters (Young's modulus, Poisson's ratio), allowing for the change in the characteristics of durability of composite material for the hull structure element are determined by introducing the reduction factors in accordance with the Rules of the Russian River Register;
- strength calculation for the structural element, where the defect was identified, is performed for an integral state; strength calculation for the structural element, where the defect was identified, is performed in the presence of a defect;
- the obtained value of the stress in the ships hull structure element of composite for the case of its integral state is compared with the critical stress determined with due regard for changing the characteristics of composite material durability in the process of operation to verify a design scheme of the structural element;
- the obtained value of the stress in the delaminated element of ship hull structure of composite is compared with the critical stress determined with due regard for changing the characteristics of composite material durability in the process of operation;
- the obtained value of the stress in the ship composite hull structure layered element is compared with the critical stress calculated from the failure conditions.

The limit of the structure strength loss is considered to be achieved when the geometrical parameter (area) of the internal defect such as delamination becomes above the value at which the current structure stress exceeds the maximum permissible level set by design standards. Strength limits of fiberglass at compression, tension and shear, reduced in accordance with the expected effects of operational factors, or the Eulerian bond stress, determined considering the shear, are taken as dangerous stresses. Assignment of dangerous stresses for ship structures made of composite materials is differentiated, depending on the operating conditions of a bond. Standard values of dangerous stresses take into account the duration and nature of the load effects, as well as changes in workability of the structures with different reinforcement depending on these factors.

Assessment of the structure strength property changes involves a comparison of its strength tested in accordance with the applicable design standards for a new hull, and the strength properties of the same structure, calculated with due regard for the presence of internal defects such as delamination in it occurring during operation and having a certain area. It is made simultaneously in two ways:

- by calculating the normal rated operating stresses caused by local bending at the let-go discretely, without considering the border areas, and comparing the obtained stress values with the maximum permissible stress values calculated taking into account the composite aging for the particular hull bond;
- by substituting the defect area size measured with a non-destructive test instrument in the Griffiths formula or the Irving formula and calculating the critical stress value, assuming that the defect size of the area is critical.

If the value of obtained critical stress exceeds the permissible stress limit calculated taking into account the composite aging for the given hull bond, defect size exceeds the limit [3].

Design features of hulls made of composite materials make it possible to apply the provisions of the theory of thin shells. For the purpose of calculating the local strength each hull element can be considered as a single shell. The entire surface of the hull and topsides is split into a family of multilayer shells. There is a calculation technique for each of them (Fig. 3).

The above-mentioned family of shells allows describing almost any surface of the ship hull and topsides made of composites with a sufficiently high degree of certainty. Being quite conditional, this breakdown at the same time allows simplifying the task within the limits of reliability.

In the actual calculation of shells the real anisotropic structure may be replaced by an equivalent orthotropic one with regards to its mechanical properties, having the same normal elastic moduli and Poisson's ratios in different directions. Multilayer structure element is regarded as a plate or shell composed of *n* layers made of orthotropic materials (Fig. 4). The method of anisotropic structure calculation based on reducing it to the orthotropic one allows solving a number of engineering problems with accuracy sufficient for practical purposes [2].

The analysis of multilayer shells made of materials with different elastic characteristics of structural layers and different elastic properties of each layer in different directions requires calculating stiffness of each layer. The core of unit stiffness transformations is that in the general case of constructively multilayer shells with orthotropic layers, different in geometrical sizes and materials, the elastic properties are reduced to the conventional isotropic material of the inner layer. Stiffness parameters of the structure are reduced to the midsurface of the shell. In the shell calculations when deriving formulae the influence of the convergence of external and internal layers is neglected allowing for considering the filler modulus of elasticity to be equal to infinity in the direction normal to the midsurface. Normal filler elasticity modulus is assumed to be zero, i.e., only data carrier layers are introduced in the expression for the flexural stiffness of the three-layer structure. Anisotropy is taken into account by using the reduced elastic modulus and Poisson's ratio, calculated as the geometric mean of these values in the directions of the coordinate axes of the composite material [2].

For example, the value E^i_r is determined for the case of material anisotropy for the bilayer structure plate or a three-layer structure with a light filler according to the formula:

$$E_r = [E_{1u} E_{2u} E_{11} E_{2н}]^{1/4} \quad (1)$$

where $E_{1u}E_{2u}E_{1l}E_{2l}$ are the moduli of elasticity in directions respectively for the upper and lower layers.

For orthotropic panel Poisson's ratios can be defined as:

$$\nu_u = [\nu_{1u} \nu_{2u}]^{1/2} \quad (2)$$

$$\nu_l = [\nu_{1l} \nu_{2l}]^{1/2} \quad (3)$$

Where ν_{1u}, ν_{2u}, ν_{1l}, ν_{2l} are Poisson's ratios in directions respectively for the upper and lower layers [2].

When the middle layer material is dispersed and of law stiffness there mutual shifts of outer and inner layers of the shell can occur. There is a technique, which allows taking into account non-linear transverse shear deformation.

Below there are examples (Fig. 5) of cross sections of the hull made of the composites and computational models developed taking into account the structural units, reinforcement schemes and applied processes of forming boat hull structures according to the technical documentation GNPRKTs "Central Design Bureau "Progress":

- keel area (200 mm on each side of the keel line) , bilge zone (250 mm above and below the bilge line), bottom plating between steps, board, deck without reinforcements, the hull bottom abutment to the transom (500mm forward of the junction line) is an absolutely rigid plate of a two-layer structure;
- board, deck in the reinforcement area is an absolutely rigid plate of three-layer structure with a light filler;
- transom is an absolutely rigid plate of a three-layer structure with a tension stiff middle layer.

In these models the anisotropy of the material is taken into account according to the scheme described above.

The structure layer obtained by spraying is considered to be isotropic. The hull shell surfaces are considered as plates, rigidly embedded in the support contour (keel line, line of board knuckle, line of board and deck joint, line of transom contiguity), and freely supported on open zigs (steps, decorative board zigs etc.). The definition of "zig" is a common technical term and represents a curved or angular protrusion of the surface of the material.

Stresses in the *i*-element of the absolutely rigid whole plate are defined as:

$$\sigma^i = \frac{M_b^i E^i{}_r (z - z_0)}{D^i} \qquad (4)$$

where M_b is a bending moment in the center of the plate or in the support section;
E_r is a reduced elastic modulus;
z is half the distance between the layer midsurfaces;
z0 is the displacement of the neutral surface from the midsurface;
D is the cylindrical bending stiffness.

The reduced elastic modulus is determined as:

$$E_r = [E_u E_l]^{1/2} \qquad (5)$$

where E_u, E_l are the elastic moduli of the upper and lower layers.

The cylindrical bending stiffness for the whole bilayer plate is determined as:

$$D = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_u \delta_u}{1-\nu_u^2}(\delta_l + \frac{\delta_u}{2} - z_0)^2 + \\ + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} + \frac{E_l \delta_l}{1-\nu_l^2}(z_0 - \frac{\delta_l}{2})^2 \qquad (6)$$

where δ_u, δ_l are the thicknesses of respectively upper and lower layers;
$\nu_в, \nu_н$ are the Poisson's ratios for respectively upper and lower layers [2].

Cylindrical bending stiffness for the entire asymmetric sandwich plate with light filler is determined as:

$$D = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_u \delta_u}{1-\nu_u^2}(H - z_0 - \frac{\delta_u}{2})^2 + \\ + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} + \frac{E_l \delta_l}{1-\nu_l^2}(z_0 - \frac{\delta_l}{2})^2 \qquad (7)$$

where H is a height of the plate cross section [2].

The cylindrical bending stiffness for the entire asymmetric three-layer plate with a rigid tensile middle layer is determined as:

$$D = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_u \delta_u}{1-\nu_u^2}(H - z_0 - \frac{\delta_u}{2})^2 + \\ + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} + \frac{E_l \delta_l}{1-\nu_l^2}(z_0 - \frac{\delta_l}{2})^2 + \frac{E_m \delta_m^3}{12(1-\nu_m^2)} + \\ \frac{E \delta_m}{1-\nu_m^2}(\delta_н + \frac{\delta_m}{2} - z_0)^2 \qquad (8)$$

where E_m, is the elasticity modulus of the middle layer;
δ_m, is the thickness of the middle layer;
ν_m, is the Poisson's ratio of the middle layer [2].

Stresses in the *i*-element of the absolutely rigid delaminated plate are determined as:

$$\sigma_{del}^i = \frac{M_b^i E^i{}_r (z - z_0)}{D_{del}^i} \qquad (9)$$

The cylindrical bending stiffness for delaminated bilayer plate is determined as: [2]

$$D_{del} = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} \qquad (10)$$

The cylindrical bending stiffness for exfoliated asymmetric sandwich plate with a light filler is determined as: [2]

$$D_{del} = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} \qquad (11)$$

The cylindrical bending stiffness for delaminated asymmetric sandwich plate with a rigid tensile middle layer is determined as: [2]

$$D_{del} = \frac{E_u \delta_u^3}{12(1-\nu_u^2)} + \frac{E_l \delta_l^3}{12(1-\nu_l^2)} + \frac{E_m \delta_m^3}{12(1-\nu_l^2)} \qquad (12)$$

Regarding the complicated configuration of defects with some degree of certainty the defect size can be represented as:

$$l = \sqrt{S_D} \qquad (13)$$

where S_d is the defect area determined with a flaw detector;

Then using the Griffith's criterion the formula for calculating the critical stress in the area of the defect location is:

$$\sigma_c = [\frac{\gamma E_r}{\pi (S_D)^{1/2}(1-\nu^2)}]^{1/2} \qquad (14)$$

Using the Irwin's criterion the formula for calculating the critical stress takes the form:

$$\sigma_c = K_c [\frac{1}{\pi (S_D)^{1/2}}]^{1/2} \qquad (15)$$

The values of γ or K_c, determined experimentally, are taken from the reference literature [3].

The condition for providing structural strength in the delaminated zone can be written as:

$$\sigma_{del}^i \le \sigma_0 \qquad (16)$$

Condition for defect non-stretching can be written as:

$$\sigma_{del}^i \le \sigma_0 \qquad (17)$$

In case of failure conditions (15, 16) it can be concluded that the defect reaches the size, at which under operating loads its steady growth can occur.

It is known that during the development of the delamination to a value less than some critical one, some residual elastic commissures remain between the edges, reducing operating stress in the delamination zone. Only reaching a certain critical distance between the layers these commissures become completely destroyed and layers of composite no longer somehow interact with each other. Due to the presence of the commissures calculating formulae provide a margin in a safe direction and, based on the calculations, the requirement of the hull construction repair is imposed long before its destruction.

SOLUTION

To test the method operability the calculation of the changes in the mechanical properties of the ship hull structure made of composites for the boat "Aqualine 210" produced by GNPRKTs " Central Design Bureau " Progress " (Samara , Russia) was carried out using the computer program Microsoft Excel. The technical documentation including assembly drawings of the ship hull was handed over by the manufacturer to the Moscow branch of the Russian River Register, which is the technical supervisor of this project vessels.

The calculations were performed for internal defects, such as delamination of technological and operational nature with the area of 440 mm^2, located in the same spot on the bottom grillage, near the bilge. Calculations were performed for three cases. In the first case the plate in the new hull containing a defect such as a delamination of the specified size and technological nature was considered (Fig. 6). In the second case, the plate of aged composite at the end of its service life (life cycle of the ship) containing the defect area of 440 mm^2 of operational nature (Fig. 7) was considered. The changed mechanical characteristics of the composite were calculated by the Rules of the Russian River Register [10]. In the third case, the possibility of new plate composite failure in the area of specified size defect of technological nature was assessed (Fig. 8). Failure was considered possible when the current stress reached the critical stress value. In the first two cases, for correct determining the value of the current stress, calculations were performed simultaneously and for entire sections of the plates in the vicinity of the defect. The calculation was performed using the Microsoft Excel program. The calculation was performed in the units of metre-kilogram-force-second system due to the fact that the coefficients in the equations of the plate bending and empirical coefficients in other formulae are obtained for physical quantities in these equations having this dimension.

CONCLUSIONS

The calculation show that conditions of strength are provided and there is no failure on the new hull bottom grillage in the delamination area of 440 mm^2. At the end of the hull lifetime (approximately 18 years after manufacturing) the current stress in the delamination area exceeds the allowable one more than 1.5 times, and the critical stress - more than 2.5 times. That is, structural strength and integrity requirements are not met, which may lead to the hull failure under normal operating conditions. Therefore the boat body requires proper maintenance.

Application of the above method makes it possible to perform the necessary calculations and give the necessary recommendations to several dozens of defects within one working day, so the process is workable for professionals involved in determining the technical condition of the hull made of composites.

The stated method of calculating the changes in the mechanical characteristics of the ship hull structures made of composites in the zone of delamination is used in the technique of assessing the technical condition of the hull made of composites, protected by patent of the Russian Federation № 2354964.

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Fig.1. *Macrograph of composite structural element, comprising delamination defects (From the site http://www.medus.com.ua)*

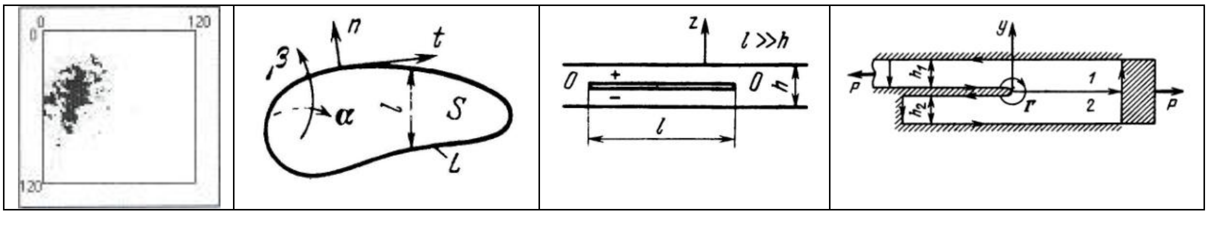

Fig.2. *Basic models of delamination defect (After Cherepanov G.P.).*

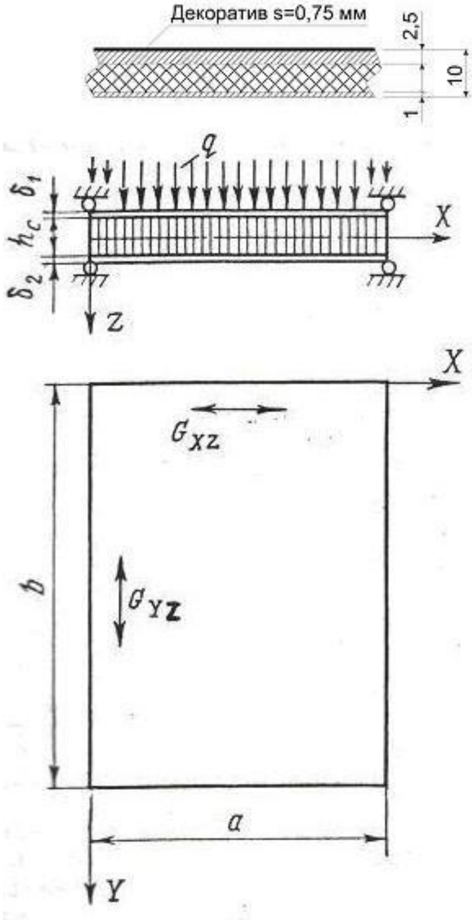

Fig.3. *An example of a design scheme of a flat sandwich plate*
with light middle layer

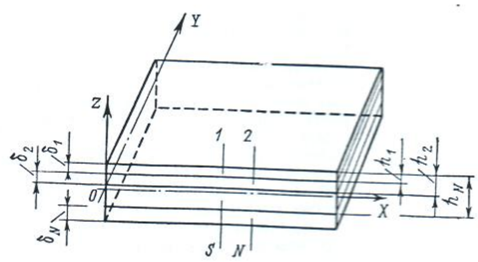

Fig.4. *The element of the multilayer structure*

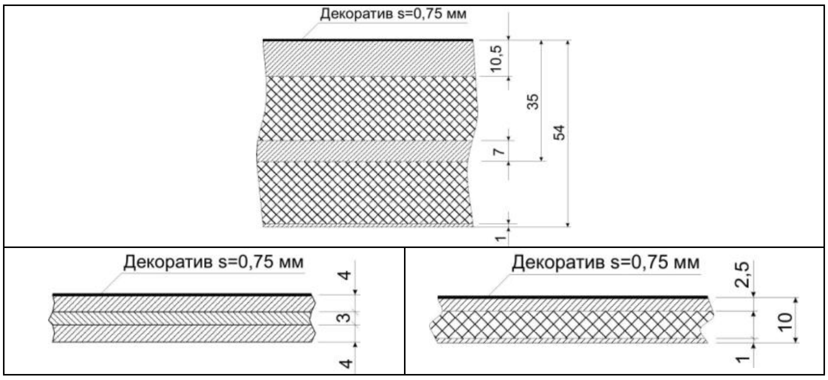

Fig.5. *Samples of sections of the multilayer of the ship hull shell of composites*

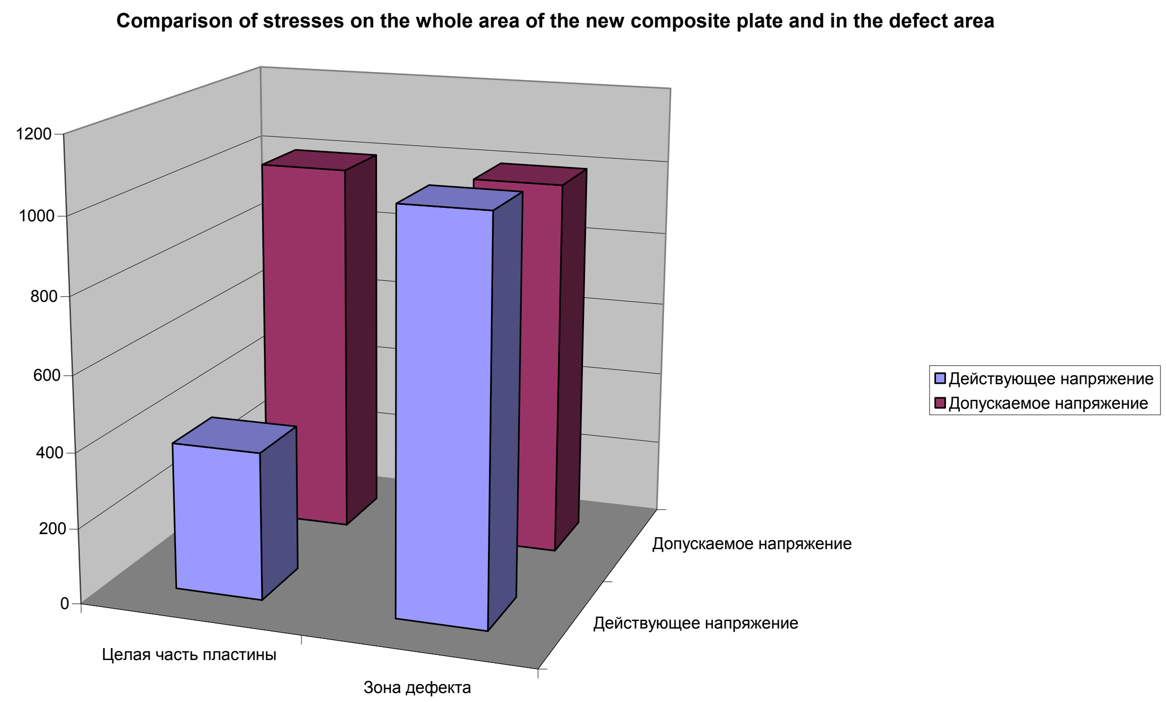

Fig.6. *Current and the allowable stresses in the new whole plate of the composite and in the area of the defect*

Действующее напряжение – current stress
Допускаемое напряжение – allowable stress
Целая часть пластины – whole part of the plate
Зона дефекта – defect area

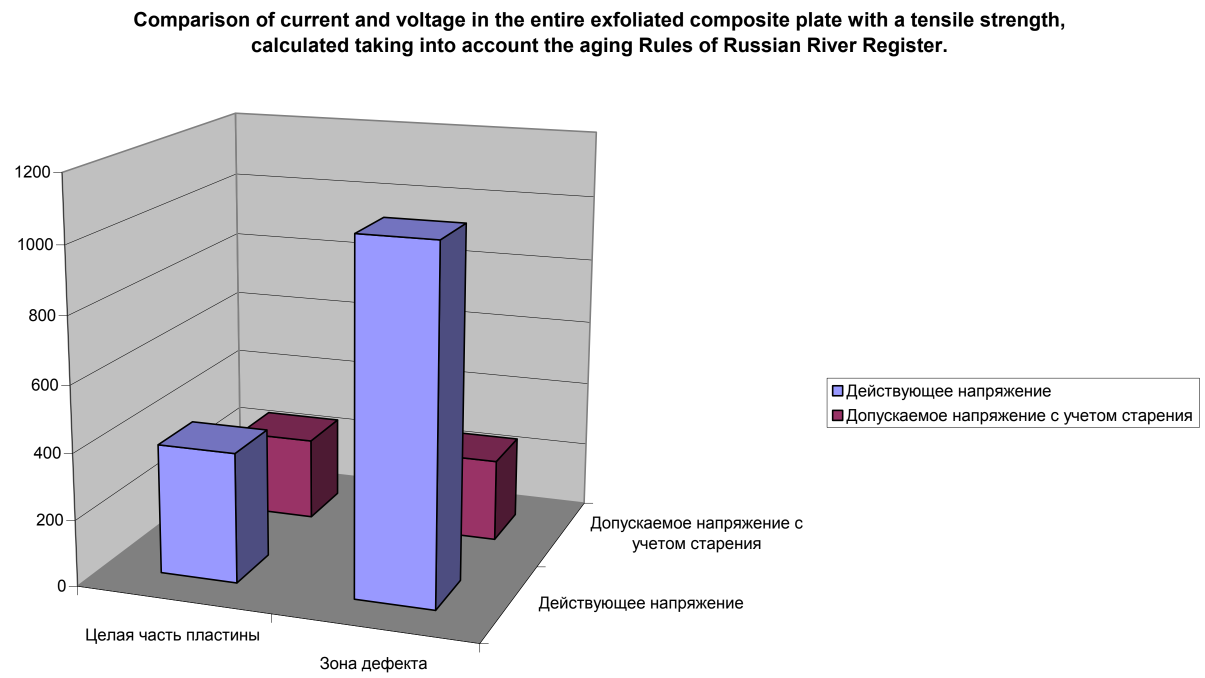

Fig.7. *Current and the allowable stresses in the whole plate of composite and in the area of the defect considering aging according the Rules of the Russian River Register*.

Действующее напряжение – current stress
Допускаемое напряжение – allowable stress considering aging
Целая часть пластины – whole part of the plate
Зона дефекта – defect area

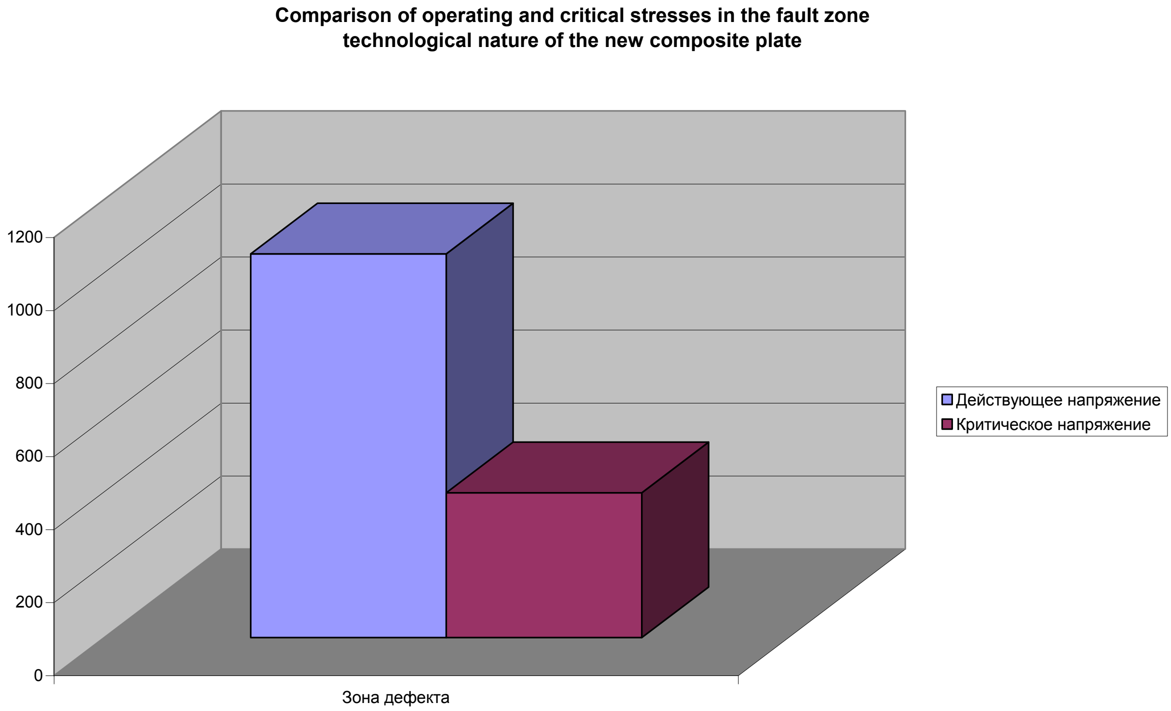

Fig.8. *The current and critical stresses in the new plate of composite.*

Действующее напряжение – current stress
Критическое напряжение – critical stress
Зона дефекта – defect area