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Structural Strength of Laminated Glass

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The subject area "structural strength of materials" is defined generally as a complex of strength characteristics of materials and structural elements, obtained under special mechanical tests. It is shown that these tests should take into account not only the physical and mechanical properties of the material, but technology, blank processing, sphere of application, the influence of shape and sizes of elements as well as of their specific loading and operating conditions. Methods for evaluating the structural strength of glass as a linearly elastic material with high sensitivity to technological defects and operational damage are discussed in the paper. Some results of the study of the strength of elements of architectural and bulletproof laminated glass are given. The sizes of technological defects such as cracks in large-sized building elements are determined on the basis of the results of tests of sheet glass plates on bending. The bending strength of sheet float glass with a thickness up to 10 mm reinforced with modification of the glass surface using various industrial technologies is considered. Some methods and results of experimental study the features of the change in the strength and rigidity of laminated armored glass under multiple ballistic tests are also presented.

Keywords: Glass, Structural Strength, Laminated Glass, Secant Effective Modulus of Elasticity, Post-Failure Strength, Post-Failure Rigidity, Local Loading, Impact load

1. Introduction

Determination of the guaranteed level strength and fracture resistance for glass structural elements encounters the problem that the strength characteristics of glass given in the reference literature do not always correspond to the actual limit state of the structural element. This problem becomes especially important as due to the progress in manufacturing technology brittle materials such as glass are increasingly used in load-carrying architectural structural elements, aircraft and military engineering. Therefore, it is important to develop the scientific principles allowing to understand and to determine structural strength of glass, taking into account the distinctive features of its mechanical behavior under different load conditions and the influence of determining factors, which can significantly and often unpredictably change fracture resistance and reliability of structural elements.

The subject area “structural strength” arose in the middle of the last century. Friedman (1952) noted that the discrepancy between the average standard values of the tensile strength of metals and structural strength as the maximum resistance implemented in the structural element, usually due to the influence of three groups of factors: technological, structural and operational. It is emphasized that the strength values obtained on various standard and special samples should be considered as output for a more precise assessment of the real elements structural strength, which may be lower or higher than one for sample.

Now there is no clear definition of "structural strength of the material". As usual it is considered as a complex of mechanical properties, which provide reliable and long-term work of the material under operating conditions. In our view, this understanding of "structural strength" is not sufficiently complete, and is close to the traditional definition of the strength of materials in different operating conditions. It does not take into account size, shape, loading conditions.

According to Pisarenko (2011) definition “The structural strength of some material we understand as material ability, from which structural elements of appropriate shape and size are made, to resist external influence“. In our opinion, this definition is universal for all classes of materials and it corresponds to the subject area, the conceptual graph of which is shown in Fig.1. One can see that the structural strength of material depends not only on its physical and mechanical properties, but also on the method of its production, further processing in the chain blank - end product, function, shape, size of the element, as well as operating conditions of: the heat loading, time and environment. In order to assess and guarantee the structural strength, a chain of tests is required (see Fig. 1): from testing of small-scale samples to full-scale tests of final product.

The effect of each factor of the subject area “structural strength” for brittle materials as glass significantly and indefinitely increases. This is due to the fundamental differences of this class of materials, such as:

- These brittle materials are linear-elastic
- Limit state of brittle materials is defect – sensitive and there are a lot of surface defects in initial state of glass element, as well as technological, operational defects and damages that significantly and unpredictable affecting the strength
- Due to the extremely low fracture toughness of glass ($K_{Ic} = 0.5...0.7\text{MPa}\sqrt{\text{m}}$), the critical size of defects for carrying structures can be 10...100 μ m, which is several orders smaller than the size of critical cracks in metal structures
- In the result of absence of plastic and viscous deforming mechanisms and low fracture toughness the failure of glass elements is brittle, occurs suddenly with possible negative consequences
- Glass is characterized by a much greater resistance to compression than to tension
- Due to the influence of different surface defects and operation damages, the strength values for glass elements are statistically inhomogeneous
- For a technical glass made by the use a different production and strengthening technologies, the bending strength can range from 10 MPa to 2000 MPa
- In contrast to most of structural materials, it is impossible to determine the value of glass structural strength by applying correction coefficients and to guarantee it using a safety coefficient of strength, when the basic value of strength is given by manufacturer of taken in reference literature.

As a result there are no structural strength values for glass guaranteed by manufacturers.

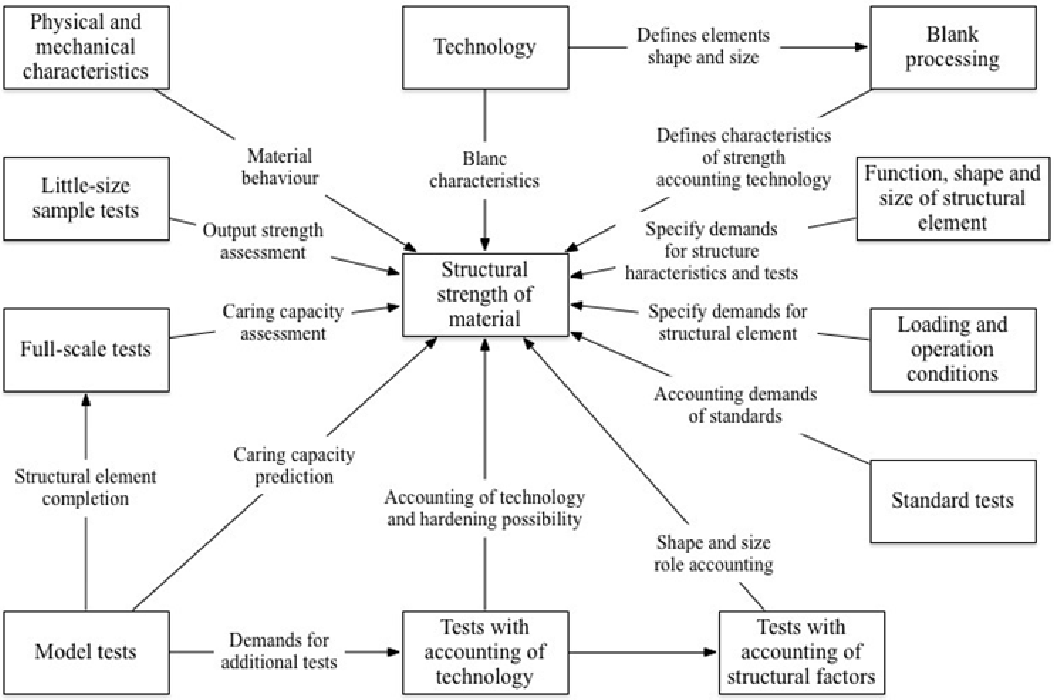


Fig. 1 Conceptual graph of the subject area “Structural strength of material”.

The continuation of Pisarenko’s (2011) quotation concerning brittle materials is: "As for material such as glass, which, in contrast to such traditional material as steel, has a number of specific features, its use as structural material is limited by structural elements, which are under compression". Such a statement suggested that application of glass as a specific structural material is promising for such engineering structures, where due to operating conditions or application of a complex of special technical solutions; the conditions of compression are realized. This idea was effectively implemented when creating various types of shells for deep-water devices that operate at high hydrostatic pressure (Fig. 2) (Pisarenko et al. 1978; Rodichev 2010).

Basing on the results obtained by use the special complex tests of glass tubes in hydraulic camera under pressure to 30 MPa it was shown that high compressive strength of glass gives a possibility to provide the necessary reliability of the strong housing for sea current meter at the depth up to 2000m. The structures of hermetical metal-glass joints and other elements of this device were developed using special experimental technique taking into account the specific mechanic behavior and experimental regularities of structural strength of glass in extreme marine operating conditions under cyclic and long-term loading (Fig.2).

The greater use of glass due to the progress in the technology of large-scale float glass production, the implementation of methods for glass element strengthening as well as improving the technology of laminated glass requires the development of structural strength aspects for another load conditions, including those, when tensile stress under static and dynamic load is present. The influence of scale factor on strength and fracture of laminated architectural glass elements under bending is actual problem of structural strength of glass (Veer and Louter and Bos 2008; Rodichev and Veer 2010). The concepts of structural safety, post- failure resistance and post-failure strength for laminated architectural glass are developed by Bos (2010). The method to evaluate the safety of glass elements based on four properties: damage sensitivity, relative resistance, redundancy and fracture mode was proposed.

Fig. 2 Strong cylindrical shell of underwater oceanographic device made of glass tube.

Laminated aviation and armored glazing is exposed to local impact loads, causing the destruction of some layers of glass in extreme operation conditions. These elements need to have not only high initial strength but the certain post-failure strength and workability. So the actual task is to estimate the residual strength and ability to maintain a sufficient load-bearing capacity of the damaged glazing structures under further static and dynamic loads. It is important to take into account that their post-failure (supercritical) deforming with damaged glass layers under intensive local loading and in the impact by bullet may be quasi-brittle with significant influence of mechanisms of non-linear viscous deformation.

Some methods and results of studying the structural strength of glass as a linearly elastic brittle material with high sensitivity to technological defects and operational damage are discussed below. Section 2 shows some results on the strength of architectural glass taking into account the scale effect on the statistical characteristics of strength. The sizes of technological defects such as micro-cracks in large-sized building elements are determined on the basis of the results of tests of sheet glass plates on bending. There are given also the data on high level bending strength of float glass with a thickness up to 10 mm strengthened with modification of the glass surface using various industrial technologies. Some methods and results of experimental study of the features of change in the strength and rigidity of laminated armored glass in the result of multiple impact loading are presented in Section 3.

2. Structural Strength of glass sheets

To take into account the scale effect on the statistical characteristics of strength , an analysis of the test results of samples made of float glass with a thickness of 8 mm and different lengths, including large-sized samples up to 3.21 m in length, was performed (Veer and Riemslag 2009; Veer and Rodichev 2011). After cutting edges of specimens were ground to form a chamfer and polished by the regimes adopted for the automated processing of large glass architectural elements on multi-spindle machines by diamond wheels with proper granularity. To assess the influence of all possible coarse defects of machining the edges within the sample working part under the same level of tensile stresses σ_{max}, the plates were tested on four point bending scheme in vertical position. The length of specimen working part (between inner loading elements) changed from 122.5 mm to 900mm. Summary length of both edges of specimens with the polished chamfer tested under maximal bending stress was 245, 450, 900 and 1800mm. So the maximum length of tested edges of specimens is comparable with dimensions of the glass building elements.

The analysis of the Weibull plots (Fig.3) for ultimate bending strength σ_b shows that the experimental results are described by piecewise linear bi-modal approximation, and deviations from the uni-modal distribution (solid line) for the lower values of probability can appear both in the direction of increase and decrease of strength level predicted by uni-modal distribution. Shape of the experimental distribution curves for all types of is reflecting the presence of two types of determinative technological edge defects.

Mean value of strength is 58MPa and 54MPa for small size plates (length 0.4 m and 0.8 m) with higher quality of mechanical treatment. The use of larger samples led to higher probability of detecting the most serious technological defects. Mean value of strength of larger glass plates decreased up to 34MPa (overall length of tested edges 1800mm) and minimal value for probability of fracture 5% (be-modal Weibull curve) is only 27MPa.

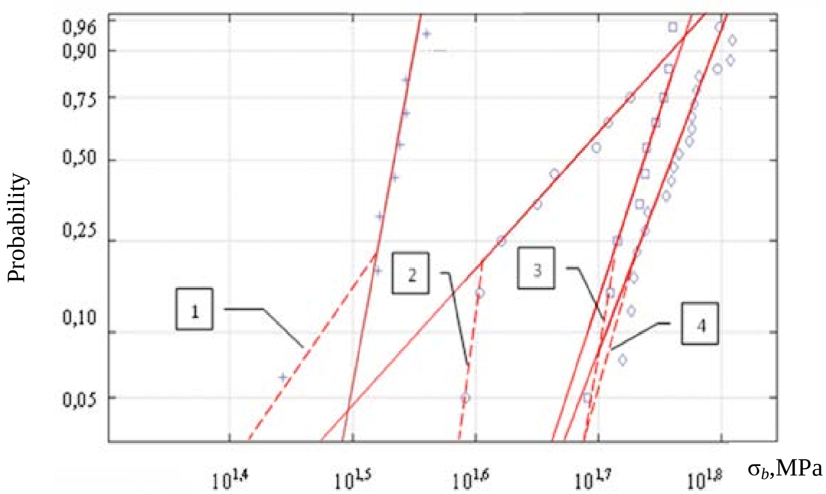


Fig.3 Weibull plots for ultimate bending strength σ_b (solid lines – uni-modal distribution, dotted lines – lower branch of bi-modal distribution) for samples with length: 1 – 3.21 m, 2 1.21 m, 3 – 0.8m, 4 – 0.4m.

The depth b_0 of semicircular and long semielliptical cracks on the edges of glass plates with different length was calculated according to linear fracture mechanics to assess the influence of scale effect on the size of most serious technological defects. Value of critical stress intensity factor K_{IC} was 0.5 $\mathrm{MPa}\sqrt{\mathrm{m}}$. It was accepted two values of geometrical factor γ – 1.9 for long semielliptical cracks and 1.128 for semicircular cracks to assess the influence of crack type on the range of critical crack depth values for specimens with the mean and minimal strength value for failure probability 5%. The uni-modal and bi-modal Weibull curves were used.

Dependences of the lower limits of the bending strength at failure probability 5% on the length of specimens obtained basing on uni-modal and bi-modal versions of Weibull plots as well as the range of critical crack depth change are shown in figure 4.

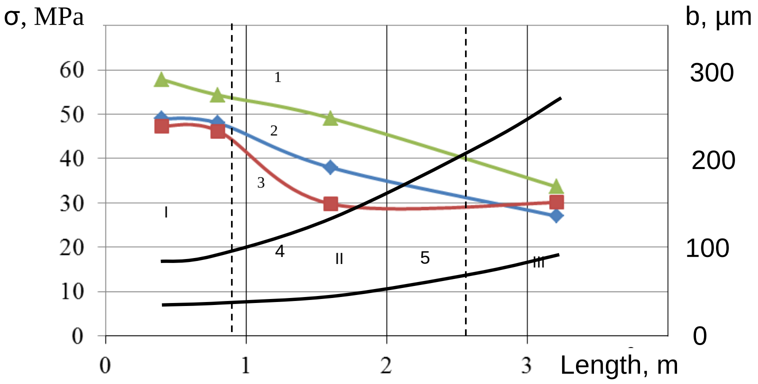


Fig.4 The dependences of bending strength and depth of critical micro-cracks on the length of standing specimens: 1 - the mean values of bending strength; 2 - the minimum values of bending strength for bi-modal Weibull curves; 3 - the minimum values of bending of bending strength for uni-modal Weibull curves (3); 4 - depth of semicircular cracks; 5 - depth of long semielliptical cracks

It can be concluded from the data in the figure 4 that depth of critical technological defects which are typical for large size architectural glass parts (range III in figure 4) is significantly larger than depth of cracks formed under processing of small and standard specimens (ranges I and II). So the results of small specimens' tests don't reflect the structural strength of architectural float glass.

It was investigated the effectiveness of various industrial methods of strengthening float glass to improve the strength of glass structural elements. The data on high level bending strength of glass plates with a thickness up to 10 mm strengthened with modification of the glass surface using technologies of tempering, chemical etching, ion exchange and combined methods are given below.

The influence of glass thickness on bending strength was studied by the method of ring on ring strength test of square specimen with length of sides 2b: 60 mm, 80 mm, 120 mm, 160 mm, 180 mm, 200 mm and thickness *h* - 3mm, 4mm, 5mm, 6mm, 8mm and 10 mm respectively. The radius of the upper punch *r* is chosen so that the load was maximally localized *r* = 7.5 mm, the radius of the lower ring support *R* varies in the range 15 ... 50 mm, depending on the size of the specimen.

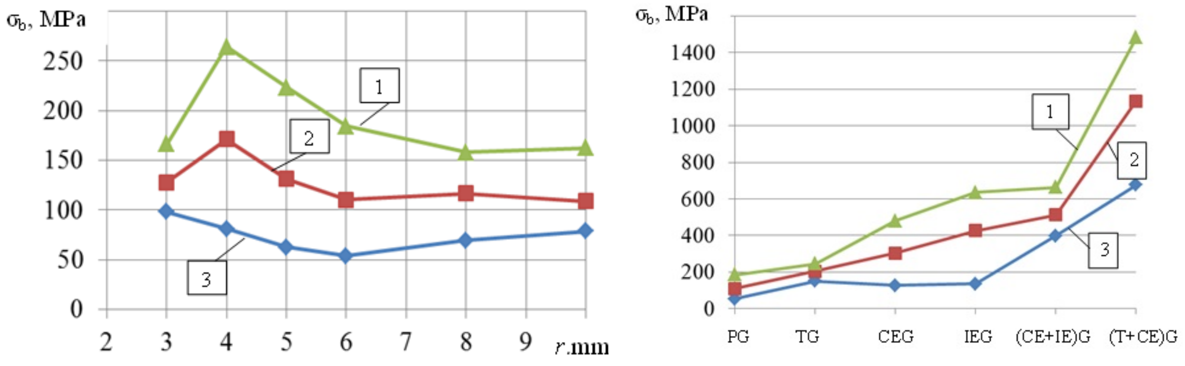
The ultimate bending stress is determined by the Eqs. (1), (2), μ – Poisson's ratio.

$$\sigma_b = 1.5\frac{P}{\pi h^2}\left[(1+\mu)\ln\frac{R}{r} + 0.5\frac{R^2}{B^2}(1-\mu)\left(1-\frac{r^2}{R^2}\right)\right] \tag{1}$$

$$B = \frac{1+\sqrt{2}}{2}b \approx 1.207b \tag{2}$$

The results of bending strength assessment for parent glass are presented depending on the thickness of the glass in fig.5,a. Maximum mean strength value 170 MPa was obtained for glass with a thickness 4mm. At the same time, the spread of strength values was maximum – 80…265Mpa.The strength of specimens of 3mm glass was in the range 100…165 MPa. Mean ultimate stress for glass with a thickness 6…10 mm was stable in the range 110…120 mm. In general, the strength values obtained were 2 ... 3 times higher than mean value of strength for plate samples of 8mm glass (length 0.4 m) with high quality of mechanical treatment tested in four-point bending (Fig.3). No influence of edge defects and a specific local loading with a small area of the working part of the samples when tested by the method of ring on ring strength test are the cause of this increase in strength of the glass.

The specimens with similar size were tested under the same loading to assess potential of different surface modification methods: tempering (T), chemical etching (CE), ion exchange – exchanging K+ for Na+ (IE), chemical etching followed by ion exchange (CE+IE), tempering followed by chemical etching (T+CE). The value of ultimate bending stress for strengthened glass depends on glass thickness and modification method. As the example, the σ_b values are shown in fig.5,b for strengthened glass with a thickness 6mm.



a) b)

Fig. 5 Maximum (1), mean (2) and minimum values (3) of ultimate stress under ring on ring bending test of glass specimens: a) strength of parent glass (PG) depending on its thickness b) strength of 6mm glass strengthened by different modification methods.

It was shown that combined methods modification of glass surface such as chemical etching followed by ion exchange and tempering followed by chemical etching have greater effect on strength for all tested glass specimens with different thickness. In this case, the bending strength of glass is increased to 400…650 MPa and to 650…1480MPa correspondingly (Fig.5b). It was found, that the strengthened effect both for chemical etching followed by ion exchange and tempering followed by chemical etching does not have the property of additivity. The results of tests of hardened glass are used to increase the durability of laminated armored glass under multiple impact loads by bullets of different types.

3. Structural post-failure strength and post-failure rigidity of laminated armored glass

Safety armored glass has multilayer laminated structure consist of rigid glass layers, viscous polymer films and other functional layers. Their mechanical behavior in the case of repeated impact by bullets of various types is characterized by an increasing level of destruction of glass and polymer layers. The study of the regularities of bulletproof glass damage is an urgent task for the development of methods for predicting the shock resistance of advanced types of transparent armor under various conditions of multiple ballistic loading. Some technical approach was developed to estimate the residual strength and ability to maintain a sufficient load-bearing capacity of the damaged safety glazing structures under further static and dynamic loads. It was taken into account that their post-failure (supercritical) deforming with damaged glass layers under intensive local loading and in the multiple impact tests by bullets may be quasi-brittle with significant influence of mechanisms of non-linear viscous deformation.

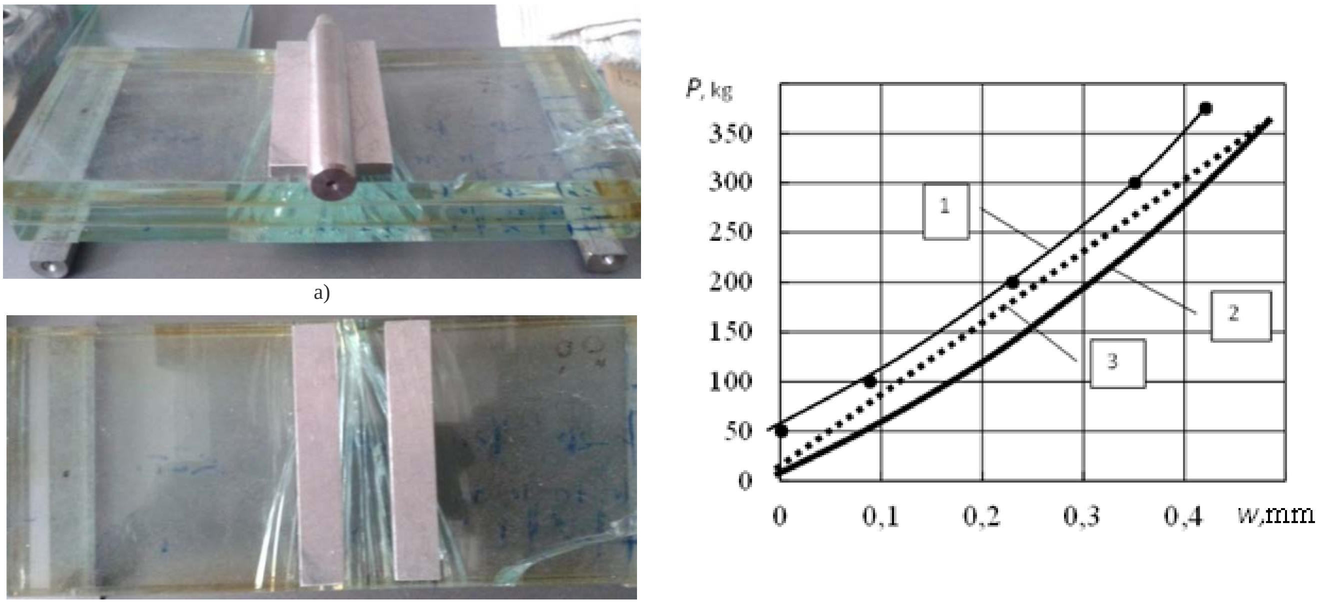
We suggested to assess the rigidity of laminated structure of plate specimens with an arbitrary number of layers, based on the test results under three-point bending conditions using effective modulus of elasticity E_{ef} for the investigated composite structure (l – distance between supports, J – axial moment of inertia) in its original state and in the locally damaged state (after a single or multiple shock loading). The position of the loading device (load P) may correspond to the maximum damaged zone or be at a certain distance in the "relatively damaged" part of the plate. An effective modulus of elasticity for laminated structure is determined by the Eq. (3) using the relation for the flexure value w:

$$E_{ef} = \frac{Pl^3}{48wJ} \tag{3}$$

Triple layer specimen 250 mmx100 mmx32 mm with every sheet glass thickness 10mm and 0,67mm PVB was tested. Loading device is in Fig. 6, a. Distance between supports is 200mm. At load P = 3755H the failure of the bottom layer of glass occurred (Fig. 6, b). The fracture of laminated glass began with the formation of through macro-cracks in the lower glass layer. The micro-crack on the edge in back surface of this layer of glass caused fracture. Non-linear loading diagram is shown in Fig. 6, c. The maximum flexure value is 0.49 mm. The secant effective modulus of elasticity at maximum loading is determined by the Eq. (3) E_{ef} = 6225 MPa, which is an order of magnitude less, than the Jung's modulus of glass. At loading P = 3755H the failure of the bottom plate of glass occurred. Calculated stress value for a beam of homogeneous glass of the same cross-section as the investigated multilayer plate is 12 MPa. This stress value excludes the failure of glass, which occurs in the test. The reason for the discrepancy is the low PVB Jung's modulus, which according to the results of Bennison (2001) decreases by 10 times in relation to one under short-term load during 1 s and is 1 MPa for the relaxation time 103 s. The calculated maximum stress in each of the layers of glass, using the model "on oil", was 41 MPa. In this model, the multilayer composition is replaced by a model of plates lying on top of one without friction. The calculated flexure value is 0.47mm, which is comparable to the experimental results.

So, to assess the limit state under static loading for short laminated multilayer elements with n plates of glass of the same thickness h and width b, we can use the Eq. (4):

$$\sigma = 1.5\frac{Pl}{nbh} \tag{4}$$



a)

b)

c)

Fig. 6 Loading device and fracture character of laminated specimen a),fracture source in the edge of bottom glass layer b) and loading diagram c) for triple layer specimen under three-point bending.

To evaluate the rigidity change after ballistic impact test (post-rigidity), the bulletproof glass specimens after a single impact load without through breakage were tested under three-point bending conditions, distance between supports is 220mm. The position of the loading device is on the maximum damaged zone on the face surface (impact region), backside (without rupture) is in the tensile zone (Fig.7). The test is repeated when the loading device is on the zone on the face surface at a distance from the impact region. This zone is characterized with distant signs of structural degradation. During the first test cycle, the compression of the damaged structure under the supports and the loading device was observed, which led to an overestimate of flexure values. In subsequent cycles, these values stabilized.

a)

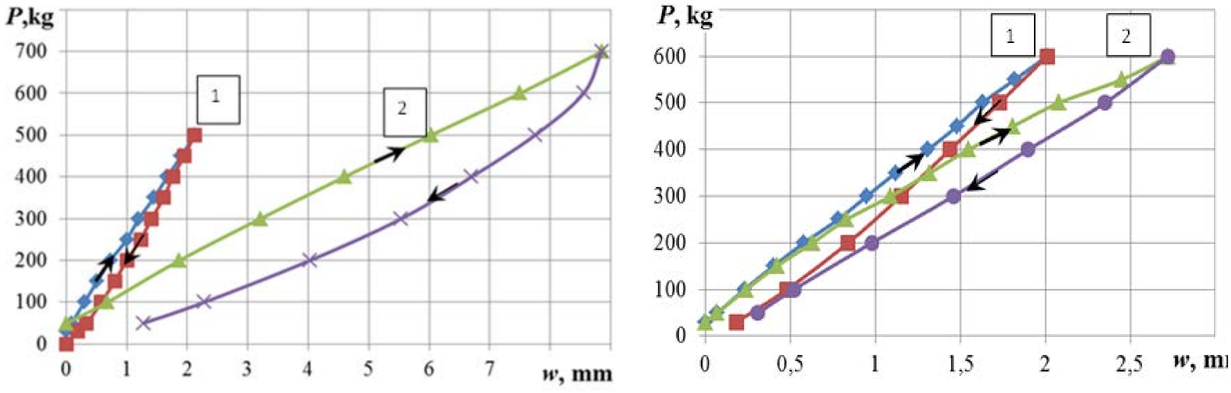
b)

Fig. 7 Three-point bending tests of the bulletproof glass specimen damaged by a single ballistic impact : the position of the loading device on the impact region a) at a distance from the impact region.

Two different laminated structures were tested:

- Straight laminated specimen 400mmx200mmx 43mm with 6 glass sheets (each thickness 4mm) and 4 polycarbonate sheets (each thickness 4mm). Laminate – EVA film (thickness 0.63mm): 4G/4PC/4G/4PC/4G/4PC/4G/4PC/4G/4G.
- Bent laminated specimen 400mmx200mmx 45mm with 7 glass sheets (each thickness 5mm) and 2 polycarbonate sheets (each thickness 4mm). Laminate – EVA film (thickness 0.63mm): 5G/4PC/5G/5G/5G/5G/4PC/5G/5G.

Deformation curves for presented in Fig. 8. Both specimens demonstrate lower post-failure rigidity when the loading device is on the maximum damaged zone compared with the loading the zone at a distance from the impact region. For specimen with four polycarbonate sheets this difference is much more. Significant nonlinearity is observed for this plate during unloading when the loading device is on the impact region (Fig. 8, curve 2).



a)

b)

Fig. 8 Deformation curves for straight a) and bent b) bulletproof glass damaged by a single ballistic impact specimens, when the position of the loading device at a distance from the impact region – curve 1; on the impact region –curve 2.

Based on the equation (2.5), the secant effective modulus of elasticity E_{ef} of the tested structures at maximum load is determined (Table 1).

Table 1: Secant effective modulus of elasticity E_{ef} of ballistic damaged structures.

Specimen	Place of load application	
	maximum damaged (the impact region)	distant signs of structural degradation (at a distance from the impact region)
laminated plate 4G/4PC/4G/4PC/4G/4PC/4G/4PC/4G/4G	172 MPa	519 MPa
laminated plate 5G/4PC/5G/5G/5G/5G/4PC/5G/5G.	437 MPa	566 MPa

For all investigated structures, effective modulus of elasticity is 2 orders of magnitude lower than the modulus of elasticity of glass, due to the influence of low-modulus structural elements as adhesive films and polycarbonate. For a structure that contains 4 plates of polycarbonate with distant signs of structural degradation E_{ef} is 10% lower than for a plate with two layers of polycarbonate. The secant effective modulus of elasticity for a ballistic-damaged structure of a plate with four layers of polycarbonate is less than 2.5 times than for a plate with two layers of PC. This shows that ensuring the rigidity of the structure strongly depends on the mechanical behavior of glass layers.

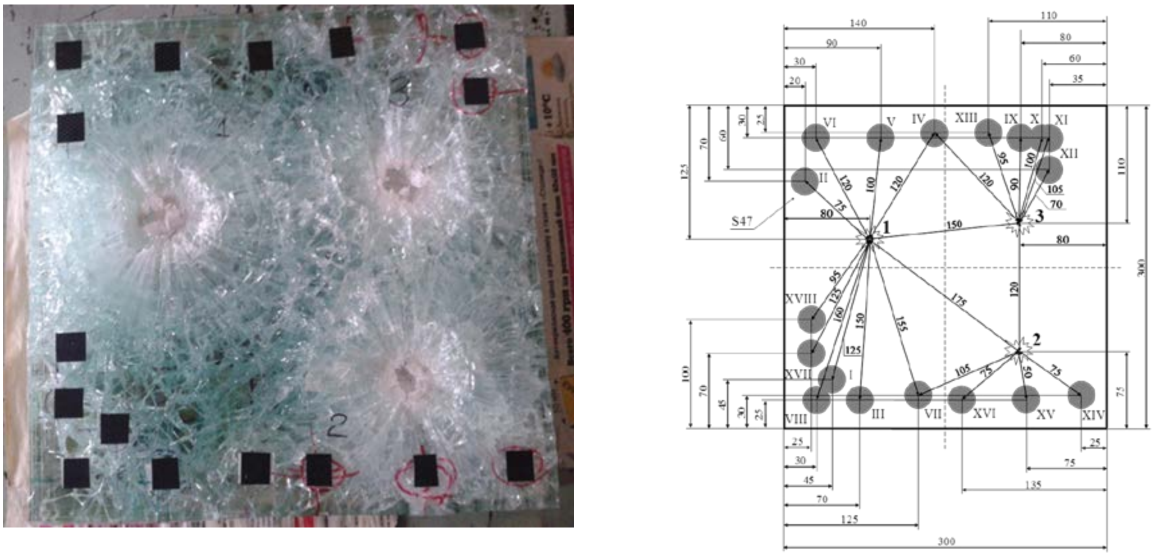
The method to assess local post-failure rigidity and post-failure strength for ballistic-damaged laminated glass at the different distance from the centers of strike is also supposed. We tested the armored glass specimen 300mmx300mmx47mm (on the base of 6mm glass) after ballistic test without rupture (three impacts). Local compression loading is realized by a punch with diameter 30mm. We marked areas for testing at various distances from the centers of bullets strikes (Fig. 9). Figure 10 shows the deformation curves “loading P – absolute compression strain δ” of the single areas of the bulletproof glass at a distance of 162 mm, 90 mm and 66 mm from the first impact region. The analysis of the curves shows a steady tendency of local post-rigidity reduction with approaching the impact region. The ultimate compressive stress σ_c in the cross-section area F corresponded to the maximum loading P, when conditions approximating to the flow under short-term loading were created, and determined by the Eq. (5):

$$\sigma_c = \frac{P}{F} \tag{5}$$

Secant effective modulus of elasticity $E_{0,02}$ is determined by the Eq. (6):

$$E_{0.02} = \frac{\sigma_c}{\varepsilon} \tag{6}$$

The values of this stress and modulus characterize post-failure structural glass strength and post-failure rigidity.



a) b)

Fig.9 Photograph a) and Scheme b) of the bulletproof glass after ballistic resistance test prepared for local compressive loads - stickers mark areas of punch location.

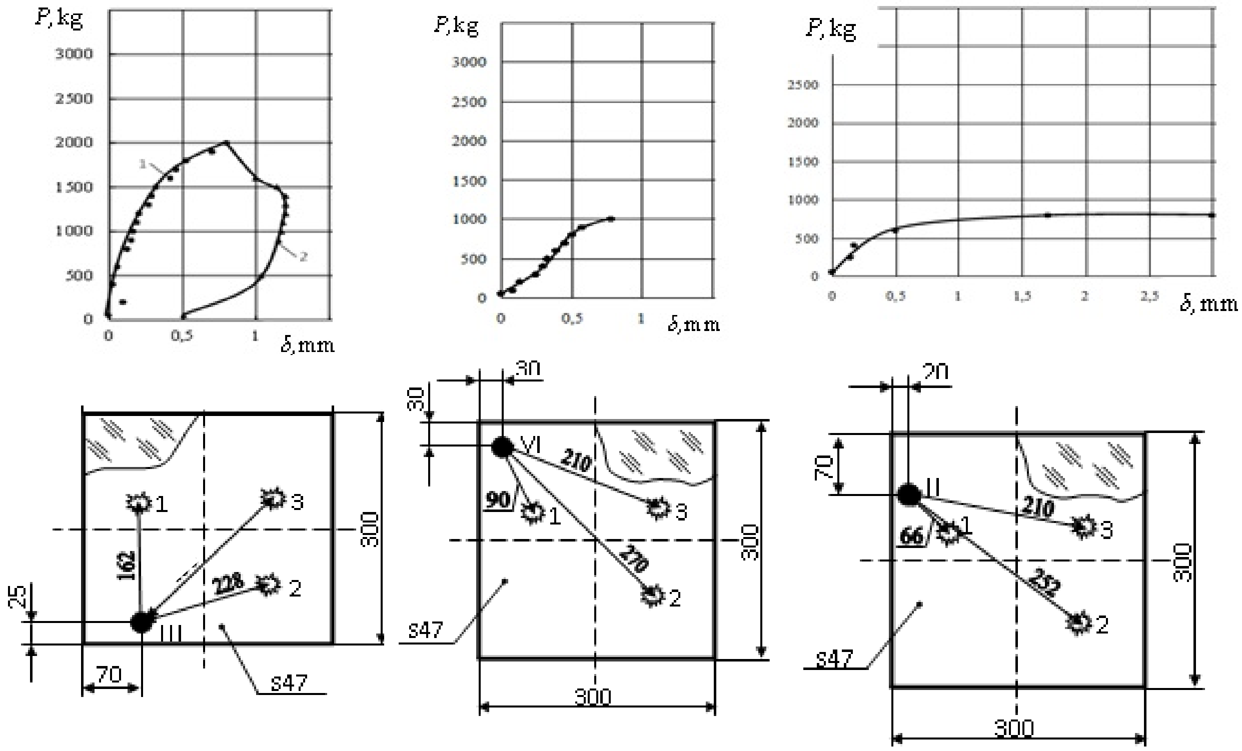
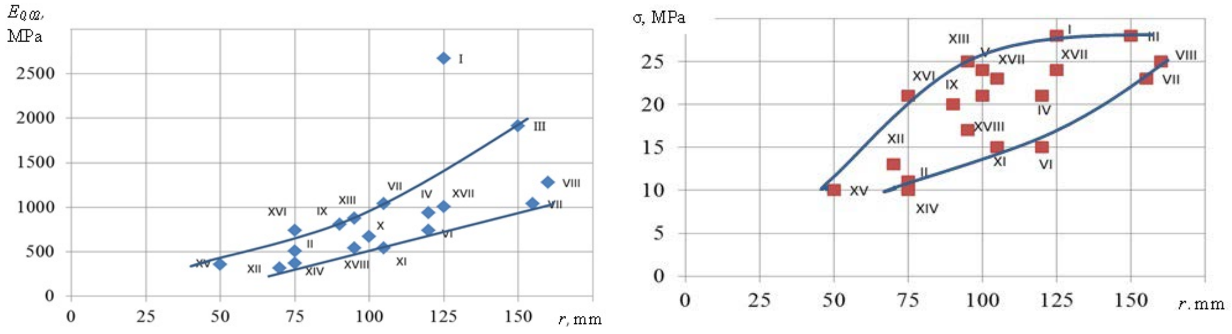


Fig.10 the deformation curves of the single areas of the bulletproof glass at a distance of 162 mm, 90 mm and 66 mm from the first impact region.

The minimum values of the secant elastic modulus are 307 MPa and 353 MPa for areas that are close to the second and third impact region. Ultimate compressive stress for these areas does not exceed 10 ... 13 MPa. This indicates an extremely large failure of bulletproof glass due to multiple ballistic loading at a limited distance between impacts. The large influence of the corner edge along with a small distance from the center of the second impact is indicated by the low values of the $E_{0,02}$, which is 367 MPa and ultimate compressive stress σ_c = 10 MPa for the area XIV. The areas I and III kept the rigidity ($E_{0,02}$ = 2666 MPa and 1905 MPa) and the maximum ultimate compressive strength σ = 28 MPa. This is due to the farthest distance from the impact region - 125mm and 150mm. It is found that all values that characterize the post-failure rigidity and the post-failure structural glass strength after multiple impact loading are in some region, limited by the curves “Secant effective modulus of elasticity $E_{0,02}$ – distance to the nearest impact region *r*” “ultimate compressive stress σ_c – distance to the nearest impact region *r*”, shown in Fig. 11.



a) b)

Fig.11 The region for the post-failure rigidity a) and the post-failure structural compressive strength b) for damaged areas of ballistic tested bulletproof glass.

The results can be used to improve bulletproof glass and methods of edges and angular areas structural strengthening.

4. Conclusions

The analysis and obtained results allow to define the subject area "structural strength of materials" as a complex of strength characteristics of materials and structures, taking into account not only the physical and mechanical properties of the material, but technology, blank processing, function, shape and size of elements, loading and operating conditions.

To assess and guarantee structural strength the chain of testing is need: testing of small or standard specimens, model tests, full-scale tests has been.

The subject area "structural strength of brittle materials (glass)" is a specific area as demands considering the brittle nature of fracture and the dominant influence of micro surface defects such as cracks of technological and operational origin on structural strength.

The particular feature of laminated glass structures is need to ensure not only initial structural strength but post-failure structural strength and post-failure fracture resistance. The methods to assess characteristics of post-failure rigidity and post-failure strength for damaged laminated glass are suggested.

It is shown that to determine the structural strength of glass, the developing of experimental methods of assessing the impact of numerous factors of structural, technological and operational origin is important.

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