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Fracture Resistance, Surface Defects and Structural Strength of Glass

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This paper poses the theory that the fracture resistance of basic float glass is dependent on it physicochemical properties and the surface defects formed under the float glass production, glass processing and handling at the service conditions compose the aggregate basis for structural glass strength assessment. The effect of loading conditions, constructional and technological factors on the engineering strength of glass can be evaluated in certain cases using fracture mechanics with information on the initial surface defects in glass elements. The correlation between the data on glass surface defects, fracture resistance and structural strength of glass is analyzed using the results received at the testing of different types of specimens. It is shown in the paper that quality management of the processing of glass elements gives a good possibility to control the strength of load bearing glass structures.

Keywords: Glass, Structural strength, Fracture resistance, Surface defect

1. Introduction

The structural strength of glass is an insufficiently known property that remains “non-transparent” to most specialists in glass engineering [1, 2]. The problem is that the actual strength of the glass components used is different from that measured on small standard and special test specimens [3]. The glass surface defects, stress corrosion as well as the effects of production technology must be analyzed to assess the load bearing capacity of the real glass structural parts [1-4]. All of these factors have a significant effect on the structural strength of glass.

It is shown in the paper that the parameters of crack growth resistance of basic float glass are dependent on it physicochemical properties and the production technology as well as the data on surface defects formed under the glass production, glass processing and handling at the service conditions compose the fundamental basis for an effective assessment of the structural glass strength. The influence of loading conditions, constructional and technological factors on the engineering strength of glass may be evaluated in certain cases using the kinetic theory of fracture mechanics with data on the initial surface defects in the glass building elements.

The correlation between experimental data on glass surface defects, fracture resistance and structural strength of glass under the bending is analyzed. The methods and results of fracture source study and mechanical testing of glass specimens and real structural parts are discussed. It is shown in the paper that quality management of the processing of annealed glass parts gives a good possibility to control the strength of load bearing glass structures.

The influence of some factors on the statistical heterogeneity of the actual structural glass strength values varies. It is shown that surface defects, micro-cracks, affect the heterogeneity of glass strength the most. The lower boundary of glass strength values correlates directly with the size and shape of the largest micro-cracks. The complex control of factual surface defects on the edges and in the central part of glass parts is difficult in production conditions for the present. So the glass production and processing technology may be used to guarantee the strength values correspondingly with the design requirements for glass structure.

2. Surface defects and fracture resistance of glass

Glass is a linear elastic brittle material with significant prior influence of the surface defects on the strength of load bearing glass parts. These defects were formed during subsequent stages of glass production, glass processing and handling. The combined effects make up the specific cracked surface layer which is illustrated in figure 1.

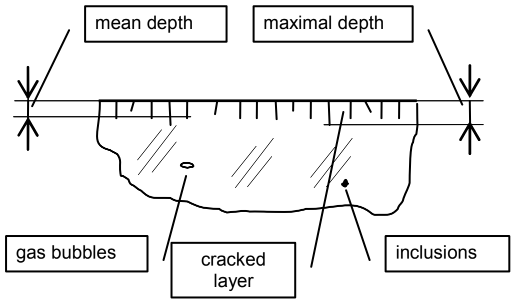

Figure 1: The micro-cracks in the surface cracked layer and internal defects in glass.

The micro-cracks placed in the surface layer are more important under thermal and/or mechanical loading than the internal technological defects like gas bubbles or inclusions as well as the defects of the micro- and nanostructure of glass. Factual statistical distribution of the micro-cracks with a different shape and depth on the glass element surface is an important characteristic of glass quality correlated directly with the structural strength of glass. Mean critical depth of the micro-cracks observed in the fracture focus of glass elements fractured under the tension and bending is about 30 μm for normal float glass. An average strength value of approximately 60 MPa is typical in this case for short duration loading. The maximal depth of the surface micro-cracks is about 100 μm. So the characteristic lower boundary of glass strength results is near the 30…35 MPa under this condition.

The size of surface defects of glass structures increases significantly during normal operational conditions. The long scratches and micro-cracks, abrasions, chipping of the edges as well as many other kinds of damage similar to the flaws shown in figure 2 may decrease the strength of glass structures. So, if the production technology and methods of handling are conducted without control of surface defects and thus the strength of glass parts, the value for the engineering strength of glass may be even less than the lower test results determined on the standard specimens in laboratory conditions.

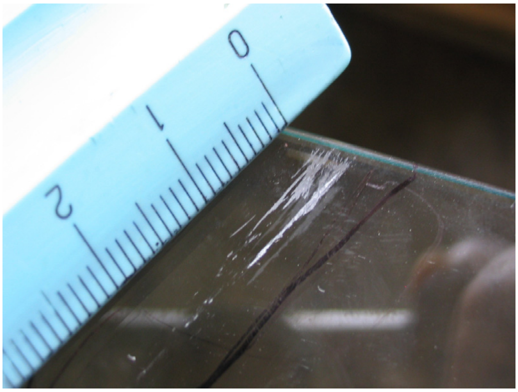

Figure 2: Some typical surface defects detected under the quality control of tempered glass plates in the production conditions.

The almost ideal linear elastic behaviour of glass is the result of the absence of plastic and viscous deformation on both macroscopic and microscopic levels and is the cause of the brittle mechanical behaviour of the structural glass elements. It has been shown that the kinetic theory of linear facture mechanics may be used to assess the micro-fracture parameters, glass strength and durability in tension and bending [5]. The calculated values for the bending strength closely approximate to experimental data on short time glass strength may be received using the equation [6]:

$$\sigma_{\mathrm{I}cr} = K_{I\,cr} / Y\sqrt{b_0} \tag{1}$$

where K_{Icr} and b_0 are correspondingly the critical value of strength intensity factor K_I and the initial depth of the micro-crack. The geometrical factor Y depends on the orientation, shape and depth of surface micro-crack in the fracture focus.

The microscopic sizes of glass surface flaws are the cause of the poor accuracy and inefficiency of non-destructive surface quality control and assessment of structural strength based on the results of surface control. Therefore, a special fractographic method for fracture source study for glass specimens and components tested under mechanical or thermal loading was developed [4, 6]. This method was used to control the depth and geometrical parameters of surface micro-cracks – fracture sources in the fractured annealed and tempered glass specimens. The scheme for the determination of limiting micro-crack parameters which are characteristic for the stage 1 subcritical crack growth using the fracture surface micrograph of a tempered glass specimen tested under the bending is shown in figure 3.

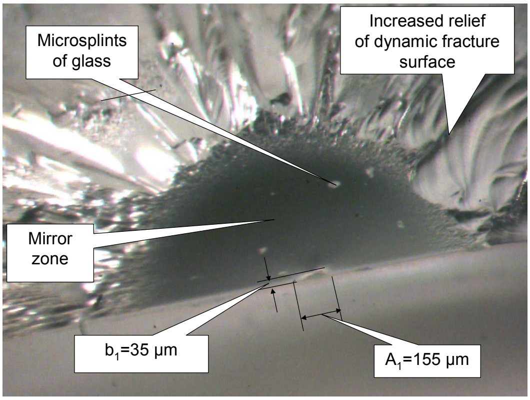

Figure 3: The analysis of limiting micro-crack parameters using the micrograph of fracture surface of tempered glass [6].

This method makes it possible to estimate effectively the shape and depth b_1 of the micro-crack in the fracture focus at the critical stage of its stable growth, when b_1 remains close to depth b_0, and the applied stress reaches its maximum value. The experimental values of factor K_{Icr} in short duration bending tests of specimens made of drawn and floated glass were in the range 0.45 to 0.55 MPa√m. The shapes of micro-cracks detected in the fracture focus were different. It was revealed that semi-elliptical and long surface micro-cracks are usually the source of a central fracture. The quarter elliptical or quarter circular geometries are typical for edge micro-cracks. The experimental values of the parameter Y calculated using the micro-fractography data and linear fracture mechanics equations were in the range of 1.36 to 2.0. The statistical heterogeneity of the data on factor K_{Icr} , parameter Y and b_1 causes the significant scatter in strength values that is characteristic for the engineering strength of glass.

3. Surface defects and bending strength of glass elements

The results of the calculations for the bending strength of glass and ceramics parts with a different depth of surface micro-cracks obtained using the equation (1) are shown in figure 4. The values of the factor K_{Icr} were in the range of 0.4 to 3 MPa√m. It was assumed in the calculations that surface semi-elliptical micro-cracks with a ratio of depth to width b/c of 0.5 were the fracture source. The values of micro-crack depth used were in the range of 10 to 100 µm, which is the usual range for float glass. Based on our experimental results, values for the factor Y of 1.5 were calculated. The numbers 1, 2, 3 and 4 show the curves for values of the factor K_{Icr} – 0.4, 0.5, 0.6 and 0.7 MPa√m, respectively. Similar ranges of factor K_{Icr} with maximal values up to 1.0 MPa√m correlate with the experimental data on float glass obtained with different testing methods using short duration loading. The curves with higher values of factor K_{Icr} correspond to ceramics parts and may be used as a basis for comparison.

The indication arrows show the strength range as 30 to 100 MPa calculated for usual sheet glass and a range of 100 to 160 MPa for high quality float glass with low defective surface (the micro-crack depth only 10 to 15 µm). The maximum strength values for a glass correspond with factor K_{Icr} = 0.7 MPa√m. The curves calculated for a higher level of K_{Icr} up to 1.5…2.0 MPa√m show the theoretical possibility to increase the strength up to 100…140 MPa even for glass parts with a micro-crack depth about 100 µm. This strength may be realized only at high loading rates under conditions where the influence of the water, moisture and other negative factors inducing the stress-corrosion process is limited. These conditions may be realized using special engineering solutions. One of these solutions was developed in the designing of an ultra-strong composite laminated glass-sapphire illuminator [7]. The thin protective sapphire layer performed the functions of a moisture barrier, contact damage protection and reinforcing structural layer to increase the breaking stress of this illuminator in bending to a range of 250 to 300 MPa. Advanced glasses with a high fracture toughness are interesting for load bearing structures. Borosilicate and quartz glasses with an increased value of K_{Icr} are more durable than soda-lime glass [5]. These glasses are used in the high-tech industry to increase the strength of critical units.

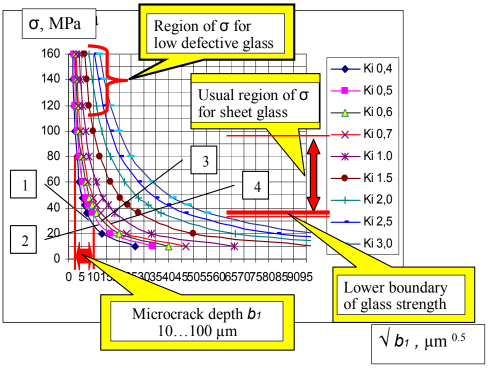

Figure 4: The calculated dependences of the bending strength of glass plates subject to the depth of semi-elliptical surface micro-crack in a fracture focus.

The results obtained from equation (1) may be used in practice only for fixed operation conditions which are identical to the tests conditions of the assessment of quantitative data on K_{Icr} , Y and b_0. These parameters are not constants and must be specified every time to take into account the actual influence of technological, constructional and operation factors. Special testing methods and large amount of sampling must be used to study these effects [1-3]. It was shown in [2,3,8,9] that to obtain useful information about the mechanical properties of industrial sheet glass it is necessary to test not less than 25 to 30 specimens. This will provide the means to analyze the information regarding the statistical levels of sheet glass strength [8]. The levels of strength with average stresses at failure 56, 81, 138, 188 and 262 MPa were defined. The first two are connected with the different abrasive actions can be eliminated by glass strengthening or glass surface protection. It is assumed that the nature of these levels was connected with the existence of fields of chemical inhomogeneity characterized by different thicknesses. The disposition of the initial surface micro-cracks inside these fields can determine the glass specimens failure stresses related to the different levels of mechanical strength. These results show that the problem of practical use of high levels of the glass strength is important and actual.

The possibility of glass strength increasing by diminution of the edge defectiveness in elements made of high quality float glass is workable. The influence of edge and centre micro-cracks with significantly different geometrical and size parameters on the engineering glass strength was shown by the statistically significant results obtained from bending tests on more than 200 pieces of cut and mechanical treated specimens 40 x 400 mm made of 6 mm float glass. The loading speed of the 4-point bending tests was approximately 1.5 MPa/s. Levels of strength with average failure stress of 47 to 61 MPa for edge and about 145 MPa for central fracture sources were determined. Minimal value of the strength for edge part of glass elements was 35 MPa. Minimal value of low defective central part of high quality float glass was increased using the accurate handling up to 110 MPa. Calculated maximal value of the depth b_0 for deep edge micro-cracks with $Y=1.36$ and $K_{Icr}=0.5$MPa√m in accordance with equation (1) was 110 μm. Minimal value of the depth of micro-cracks with $Y=1.5$ was obtained near 9 μm for the central region of test portion of high strength glass specimens. The results of the edge strength received using these specimens after their mechanical treatment – grinding and polishing on the usual production technology for building glass elements were comparable with cut specimens upon the average. The mean value of strength was 58 MPa. But the minimum value was increased up to 50 MPa. This result demonstrates the importance of edge mechanical working for increasing the load bearing capacity of glass structures. The calculated value for the edge micro-crack depth was decreased from 110 μm after the cutting up to 55 μm as the result of the mechanical treatment.

The existence of some different kinds of surface micro-cracks on the edge and in central part of glass plates as well as the influence of some other factors are the causes of multimodal Weibull plots representing statistically the variation of the engineering bending strength for these elements [9]. It was shown in the result of the tests of special 10 mm glass specimens-beams of size 1000 mm long and 100 mm wide made of annealed, tempered and heat strengthened float glass. The parties of specimens as the units of 21 to 30 pieces were made from a single jumbo sheet of glass using standard industrial production technology. The essentially bi-linear Weibull behaviour of the data on all tested types of building glass was demonstrated. It was concluded that for certain cases a certain guaranteed minimum strength can be defined. This is however dependent on edge quality, orientation of glass elements relative to load, aspect ratio and compressive pre-stress level. A Weibull plot of the results for annealed glass is given in figure 5. The lower value of strength 21.2 MPa was mentioned for standing plates (left curve) tested in the position similar to a state of building glass beams in a practice. The minimal strength of specimens tested lying under lateral bending was larger – 25.8 MPa (right curve).

The surface micro-cracks made during the mechanical working of glass plate edges are different on the arris and end face of the age. Their influence is especially important when plates of glass used in standing position. The deepest micro-cracks have the semi-elliptical shape on the arris of grinded bevel and long cut mode in the end face. The values of factor Y are about 1.5 and 1.93, accordingly [5, 6]. The maximal values of the depth calculated using the results given in figure 5 and equation (1) for factor $K_{Icr}=0.5$ MPa√m are 165 μm for the arris micro-crack and 150 μm for the end face crack. Therefore, the presence of such significant technological micro-cracks after the final polishing of the edge of glass elements is the main cause of low engineering strength of the glass. It is obvious that the strength for critical glass structures in this case will be too low if proper strength control will not be implemented widely in the glass industry.

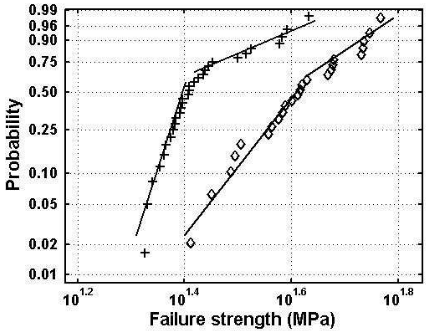

Figure 5: Weibull plot of the results for annealed glass tests.

The state of a surface cracked layer of glass is not stable after the processing of the elements as the operation conditions increase the damage. For example, the erosion of glass elements by sand particles during sandstorms or transport movement is a regular phenomenon. The progressive loss of matter on the surface affects both the optical transmission and the mechanical strength. The influence of sand impacts on glass strength was simulated in laboratory [10]. It used the Weibull distribution function to characterize the variation of the mechanical strength of a soda-lime glass in the as received state and eroded by sand blasting during 30 and 60 min. From the failure probabilities distributions, an evident drop in strength values of about 13% was noticed after 30 min and a tendency to level out with a much reduced dispersion after 60 min. The Weibull plots for the as-received state and for the 30 min eroded state presented curves with an inflection point. They were considered as bimodal forms (two straight lines) denoting the presence of two kinds of defects that control strength. The Weibull plot for the 60 min eroded state sample presented one straight line (uni-modal form) that indicates the predominance of erosion defects. That is why special anti-damaging technologies must be developed to guarantee the appropriate high-strength state of glass surface both under the processing and handling of structural elements.

High variation of strength values is not an inherent property of glass. Special experiments were conducted to show the real possibility of reducing the spread of strength values by stabilizing the shape and depth of critical surface micro-cracks. The specific 10 mm flat glass specimens with the artificial micro-crack cut shown in the figure 6 were tested under 4-point and 3-point bending. The speed of loading was about 1 MPa/s. More than 80 specimens were tested in short duration loading. The mean value of the crack depth was 320 μm and the maximum depth of the micro-crack was 350 μm. The average value of the strength was about 15.5 MPa. The variation of glass strength values did not exceed 3 to 5% if the initial shape and depth of the surface micro-cracks placed in the fracture focus of the tested specimens were stable as well as the loading speed and conditions of loading were constant. The average critical value of the factor K_{Icr} for these glass specimens was 0.5 MPa√m.

This effect of high stability of critical loads for cut glass specimens was used to study the fracture toughness of sheet glass and other kinds of glass [6]. In order to obtain stable values of cut geometrical parameters precisely controlled load values and state of the nose of roller cutter were used. Owing to high stability of the shape, size and orientation of this kind of artificial cracks relative to the tensile stress direction under the testing, this method gives a possibility to reliably study the general regularities of subcritical growth of the micro-cracks, which are similar to an ideal flat surface crack.

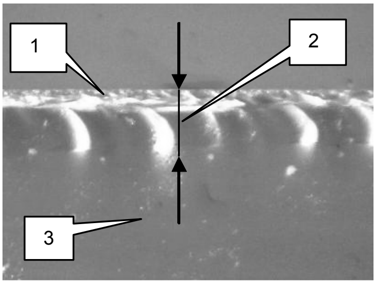

Figure 6: Fracture surface of cut glass specimen after the fracture toughness test under the bending. 1- cracked layer of glass (maximal depth of micro-cracks about 35…40 μm); 2- depth of the cut - 300 μm; 3- internal "free of defects" glass structure.

Our experimental values of K_{Icr} for drawn and float glass with a thickness 4 to 10 mm were in the region of 0.45 to 0.5 MPa√m in the bending tests with the loading speed V_σ changed in the range of 1 to 10 MPa/s. A decrease of the calculated values of K_{Ic} to 0.3 to 0.4 MPa√m was observed under long duration static bending tests of flat glass specimens with a constant value of stress [6]. This decrease of K_{Ic} calculated basing on initial crack depth b_0 and equation (1) results from sub-critical crack propagation occurring below experimental short duration value K_{Ic} under the influence of stress corrosion processes.

4. Time dependences of strength and fracture of glass

Time dependencies of strength and fracture characteristics of glass may be controlled using the experimental $K_I - V_b$ diagrams for defined types of glass under fixed operational conditions. The lifetime of glass elements under static loading is realized usually in the range of stable speeds of the crack growth V_b complied with the linear fracture mechanics with the mode I propagation. The empirical equation from [5] is considered valid:

$$V_b = \alpha \ K_I^{\ n} \tag{2}$$

where α and n are the parameters depending on the environmental conditions and the physicochemical properties of the glass. The minimal values of V_b for sub-critical stable growth of the crack in glass registered usually under static loading are in the range 10^{-10} to 10^{-8} m/s as well as the maximum values of V_b are not higher than 10^{-4} to 10^{-3} m/s [5]. The parameters α and n are assumed to be constant under fixed conditions of glass fracture testing [5]. The values of α = 0.6 m/s and n = 16 were used in [11]. The actual influence of different technological and operational factors on these parameters values is not known.

The experimental value n = 16 was obtained testing 4 mm thick glass, shown in figure 7, [6]. It was determined that the fracture toughness of glass changes significantly during the conditions of long duration loading. The factor K_{Icr} was calculated using the experimental values for the long term strength of glass σ_d and the initial depth b_0 of the artificial microcrack on the equation:

$$K_{Icr} = \sigma_d Y \sqrt{b_0} \tag{3}$$

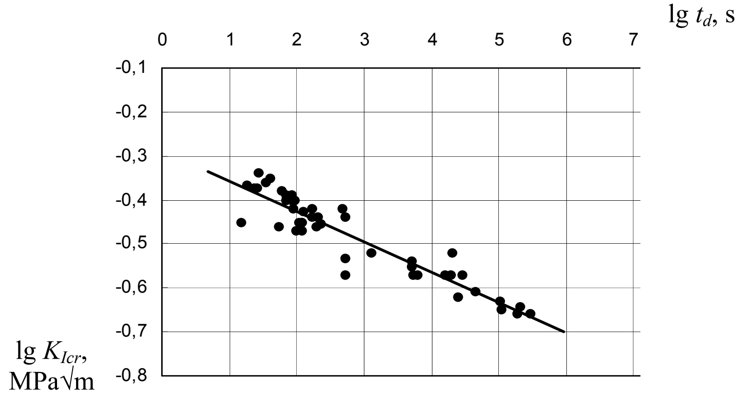

Figure 7: Fracture toughness of glass under the long duration loading in bending.

Figure 5 shows the decrease of critical value of the stress intensity factor K_{Icr} at the tests of cut flat specimens of glass 4 mm in thickness (depth b_0 =350 μm) under the long duration bending at constant load. The accuracy of experimental values of n is not high as there is a large variation of data on long duration loading failure strength of glass elements.

The subcritical micro-crack extension from the initial depth b_0 to critical value b_{cr} in the fracture moment is not considered in the equation (3). So the factor K_{Icr} is actually less than the theoretical critical value K_{IC} if the critical value of crack growth speed $V_{b\,cr}$ reaches the maximum value $V_{b\,C}$, the stress reaches the inert strength σ_C and microcrack extension is then absent. The actual ratio of K_{Icr} and K_{IC} as well as the real critical value $V_{b\,cr}$ are not known exactly. This is a subject for further scientific study. A technical approach was realized basing on the equation (2) and equations for lifetime and strength assessment for glass under short time and long time loading in compliance with [5, 11]. Based on the data on critical surface micro-crack depth the next equation may be used for lifetime t_d assessment under durable static loading with constant stress level σ_d :

$$t_d = \left[(0{,}5n-1)\alpha\sigma_d^n Y^n\right]^{-1}\left(\frac{1}{b_o^{0{,}5n-1}} - \frac{1}{b_{cr}^{0{,}5n-1}}\right) \qquad (4)$$

The correlation between the running time t, lifetime t_d, initial depth of crack b_0 and critical value of depth b_{cr} may be evaluated in the assumption that parameters α and Y are constant under different loading conditions and certain environmental conditions are kept stable:

$$t/t_d = 1-(b_o/b_{cr})^{0{,}5n-1} \qquad (5)$$

Analysis of this correlation shows that there is no actual critical stable depth b_{cr} , because the crack depth becomes unstable beginning from the values of $b \geq 1.5$ to $2b_0$ and running t is close to t_d. The fracture of glass structure becomes inevitable as a result of this. Therefore the equation (4) may be transformed for practical assessment of life time basing on results of control of the initial crack depth b_0 like this:

$$t_d{*} = \left[(0{,}5n-1)\alpha\sigma_d^n Y^n b_0^{\;0.5n-1}\right]^{-1} \qquad (6)$$

The specimens of 6 mm float glass with the surface micro-crack-cuts (b_0 = 310 $\pm$ 10 μm) were tested in bending. First ten specimens were tested under short time loading with a loading speed V_σ = 1 MPa/s. The mean value of failure stress was σ_{cr} =20.5 MPa. The second group of specimens were tested under constant loading with σ_d= 16.5 MPa. The range of lifetime to failure values was 190 to 550s. Mean value of t_d= 420 s. Based on these results the long time bending strength σ_{dl} for lifetime t_{dl}= 10^8 s (more than 3 years) using the value n = 12 and ratio was calculated using:

$$\sigma_{dl} = \sigma_d (t_d / t_{dl})^{1/n}$$

This gave a calculated value of σ_{dl}= 7.6 MPa. It is obvious that this strength reduction has a significant effect on the design of load bearing structures. Special anti-damaging technologies must be developed to guarantee the appropriate high-strength state of the glass surface both under the processing and handling of the structural elements. The use of heat strengthened and fully tempered glass elements as well as composite laminate units may be effective to increase the strength and durability of large-size building structures.

5. Conclusions

The results of this study show that the assumed engineering strength of glass can be too low if the state of the surface and strength of carrying elements will not be controlled exactly under their processing and operation.

A technological approach developed during the research gives a good possibility to control the strength of glass load bearing glass structures more effectively.

6. References

[1] Pisarenko G.S., Amelianovith K.K, Kozub Yu.I., Rodichev Yu.M., Okhrimenko G.M., Strong shells made of silicate materials.- Kiev: Naukova Dumka, 1989.-224 p.

[2] Veer F.A., The strength of glass, a non transparent value, Heron, vol 52, issue 1, 2007.

[3] Veer F.A., Rodichev Y., Glass failure, science fiction, science fact and hypothesis.- Proceedings GPD 2009, Tampere, Finland.

[4] Rodichev Yu., Tregubov N., The Challenge of Quality and Strength of the Hardened Architectural Glass.- Proceedings GPD 2009, Tampere, Finland.

[5] Evans A.G., Langdon T.G. Structural ceramics.- Pergamon Press.- Transl. on Rus. Moskow : Metallurgy, 1980.- 256 p.

[6] Rodichev Yu.M., Maslov V.P., Netychuk A.V., Bodunov V.E., Yevplov Yu.N., Bending Strength and Fracture of Glass Materials under the Different Loading Conditions.- Proceedings GPD 2007, Tampere, Finland.-P.P.615-618.

[7] Maslov V.P., Rodichev Yu.M. New Laminated Composite Materials Based on Float Glass.- Proceedings GPD 2007, Tampere, Finland.

[8] Gorokhovsky A., Escalante G.I, GorokhovskyV. Mechanical strength of float glass: test results analysis and the nature of differences.- Glass science and technology ISSN 0946-7475.-2000, vol. 73, No11, pp. 344-350.

[9] Veer F.A., Louter P.C., Bos F.P. The strength of architectural glass.- Proceedings of Challenging Glass Conference.- 2008.- TU Delft.-Delft, Netherlands.- pp. 419-428.

[10] Madjoubi M.A., Bousbaa C., Hamidouche M., Bouaouadja N. Weibull statistical analysis of the mechanical strength of a glass eroded by sand blasting.- Journal of the European Ceramic Society ISSN 0955-2219.- 1999, vol. 19, no16, pp. 2957-2962

[11] Devigili M., Flandoli F., Froli M. The Challenge of Predicting Glass Lifetime.- Proceedings of Challenging Glass Conference.- 2008.- TU Delft.-Delft, Netherlands.- pp. 331-340.