Experimental study of strength properties for the modern glass

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Abstract

Today role of glass as structural building material is constantly growing everywhere including Russia. When fenestration areas and using of new constructional methods and architectural solutions are growing, implementation of state-of-the-art glass for various purposes carries out very actively. In connection with this trend problem are raised about stress-strength properties of glass products.

During last two years several series of strength measuring tests were carried out in testing centre of the Glass Research Institute. Our tests included static central-symmetric deflection test for the following types of glass: tempered, fireproof, laminated and chemically toughened glass. Analysis of measurements was carried out under STP 12-5-78 (mean-value analysis) and EN 12603:2002 (determination of confidence interval for breakage stress with 0.1 % breakage possibility). During analysis we found interesting regularities concerned both common constructional performance of different glass types and specific features of tested glass types. Strength properties spread are found much wider than it is normal for traditional construction material. Essential increase of the samples strength after chemical toughening was proved. But also we found that spread of the strength between samples can increases too as chemical treatment result. Strength properties of the fireproof glass were proved to be neither lowers than properties of laminated glass at least, in some cases they exceeded characteristics of laminated ones.

1. Introduction and problem statement

The totally mass of the nowadays produced glass is a flat glass, which thickness is much lower than length and width. Flat glass is widely used in construction, automotive, shipbuilding, aircrafts and other fields. Traditionally role of the glass in building or transport vessels was only translucent material. Therefore the basic requirements to the glass were high light transmission, low optical distortion and high stability under environmental effects.

Today we are eyewitnesses of impressing changes in architectural basic principles. New architectural forms use large translucent areas, therefore dimensions of glass plates grow rapidly. New spheres of glass application appeared, such as glass floors, roofs, translucent barriers, façade systems and many other examples. It is not a secret in fact, that glass becomes not only translucent material but construction one as well. Some recently emerged multistory buildings have envelopes which made of glass in full.

Having regard to the up-to-date requirements, demanded from buildings and constructions, it is necessary to consider glass not only as transparency shield materials, but also as structural material meant for mechanical loads bearing. Therefore it is important to know its strength properties: allowable stress in glass, allowable deflection etc. depending on load distribution and quality of the glass itself, for example, surface conditions and defects presence inside. And significance of such data will grow in the future.

For determination of the modern glass strength properties, testing center of the Glass Research Institute carried out series of experiments with the various glass types' samples. Tests involved following types of glass: laminated glass (with fireproof capabilities), float glass and ion-exchange chemically strengthened glass.

2. Experimental procedure

In this work we used static centrosymmetrical bending (CSB) technique for determination of glass ultimate strength (damage stress). This technique described in specification STP 12-5-78 "Inorganic glass. Method for determination of ultimate strength by centrosymmetrical bending". It is based onto measuring of breakage loading by bending of sample on ring support. Loads applied in alignment with ring support by means of shaping ring. After measurements ultimate stress could be calculated from deflection and breakage load.

Testing results were processed by means of two different methods:
- STP 12-5-78 recommends calculation of mean ultimate strength of the samples and standard deviation.
- EN12603:2002 «Glass in building. Procedures for goodness of fit and confidence intervals for Weibull distributed glass strength data.»

There are two different approaches to the mechanical properties statistical estimation: from average of measured results and from Weibull-distribution with fixed low fail probability. It is well known that different institution in the various countries apply both of these approaches to the construction materials so we decided to include both of them in our research.

During the experiment 2 lots of samples were tested. Table 1 shows Lot 1composition.

Table 1. Lot 1: fireproof laminated glass. Amount of samples was 120 (of 6 types):

Label	Nominal thickness, mm	Glass construction scheme	Fire resistance of glass
E1-15-7R	7	3-1-3	EI 15/E 30
E1-15-11R	11	3-1-3-0,76-3	EI 15/E 30
E1-45-11R	11	3-1-3-1-3	EI 30/E 45/E 60
E1-45-15R	15	3-1-3-1-3-0,76-3	EI 30/E 45/E 60
E1-60-15R	15	3-1-3-1-3-1-3	E 45/E 60
E1-60-19R	19	3-1-3-1-3-1-3-0,76-3	E 45/E 60
Note: 3 – thickness of flat glass ply in mm, 1 – thickness of thermotransforming interlayer in (TTL) mm, 0,76 – thickness of polyvinyl butyral (PVB) layer in mm.			

Lot 2 consisted of float glass and ion-exchange chemically strengthened glass. Total amount of samples was 120.

- Dimensions of a sample — 280x330 мм
- Sample thickness — 4 mm or 6 mm
- Sample types: — Initial reference glass (not processed)
Glass, submitted to ion-exchange process during 2 hours (X+IE 2)
Glass, submitted to ion-exchange process during 16 hours (X+IE 16)

Before testing all samples were observed upon appearance defects presence. Tests were carried out with the help of test machine FP 100/1 with 10 ton-force load (Verification certificate № 57550/445 from 28.05.2007). Three parameters were measured during the tests: sample thickness (mm), breakage loading (kN) and deflection (mm).

3. Post-processing of observations

Post-processing of obtained results was made according to STP 12-5-78 and EN 12603:2002 (E). Calculation of confidence interval followed technique from section 8.4.1 of EN 12603:2002 (E). Tables 2.1 and 2.2 consist of average data and confidence intervals of fracture stress with 0.1% fracture probability for Lot 1 and 2 respectively.

Table 2.1. Average testing results and confidence intervals for fracture stress in Lot 1.

Sample label	Glass side	Average strength, MPa	Standard deviation, MPa	Variation coefficient, %	Ultimate strength (breakage stress), MPa	Confidence interval (upper and lower limits), MPa	
E1-15-7R	Equivalent sides	33.66	11.13	33.06%	3.99	8.25	1.34
E1-15-11R	Glass	25.45	3.73	14.64%	12.30	16.92	6.35
	Laminated glass	12.01	3.56	29.64%	1.94	4.46	0.28
	Both	19.08	7.75	40.63%	1.77	3.94	0.47
E1-45-11R	Equivalent sides	19.41	5.77	29.71%	3.51	6.20	1.36
E1-45-	Glass	20.35	5.87	28.83%	3.39	7.44	0.58

15R	Laminated glass	12.27	5.36	43.65%	0.84	2.72	0.06
	Both	16.31	6.86	42.06%	1.22	2.87	0.29
E1-60-15R	Equivalent sides	13.17	4.98	37.84%	1.48	3.10	0.43
E1-60-19R	Glass	15.13	2.17	14.34%	6.38	9.36	2.72
	Laminated glass	13.65	3.05	22.37%	3.25	6.27	0.69
	Both	14.43	2.66	18.43%	4.87	7.08	2.61
Note: Glass – force applied from the float glass side of the composite sample; Laminated glass – force applied to the laminated glass side.							

Table 2.2. Average testing results and confidence intervals for fracture stress in Lot 2.

Glass thickness, mm	Batch	Glass side	Average strength, MPa	Standard deviation, MPa	Variation coefficient, %	Ultimate strength (breakage stress), MPa	Confidence interval (upper and lower limits), MPa	
4	initial	Tin side	92.39	27.49	29.75	**17.81**	**35.43**	**4.47**
		Tinless side	52.99	13.19	24.88	**12.41**	**24.05**	**2.77**
		Both	74.66	29.58	39.63	**6.50**	**14.56**	**1.70**
	2 hours	Tin side	356.04	133.2	37.41	**33.50**	**86.92**	**6.21**
		Tinless side	313.03	109.78	35.07	**63.56**	**107.82**	**25.42**
		Both	334.54	121.37	36.28	**37.82**	**74.01**	**15.383**
	16 hours	Tin side	263	58.49	22.24	**87.13**	**140.18**	**35.62**
		Tinless side	297.14	89.54	30.13	**56.62**	**116.43**	**11.74**
		Both	279.25	74.99	26.85	**58.93**	**98.29**	**26.19**
6	initial	Tin side	63.58	26.62	41.86	**5.61**	**16.06**	**0.54**
		Tinless side	42.86	7.64	17.82	**14.06**	**23.51**	**4.12**
		Both	53.77	22.21	41.3	**4.65**	**10.68**	**1.08**
	2 hours	Tin side	209.2	118.38	56.59	**4.96**	**24.41**	**0.16**
		Tinless side	239.73	91.81	38.3	**22.29**	**60.10**	**2.75**
		Both	225.19	103.75	46.07	**12.25**	**31.51**	**2.83**
	16 hours	Tin side	225	89.33	39.7	**20.27**	**55.51**	**2.97**
		Tinless side	280.07	56.88	20.31	**87.20**	**143.29**	**30.99**
		Both	252.53	78.32	31.02	**44.76**	**78.96**	**21.12**

4. Analysis of results

It should be noted at once that glass is a very specific material from design engineer's point of view because it has high spread of mechanical properties. If this mentioned engineer is interested in durability of construction materials at least. Table 3 consists of comparative data about strength characteristics of the traditional well-known building materials.

Table 3. Design strength, MPa

Material	Tensile strength, Rp	Compression strength, Rc	Shear strength
Steel grade ВСт3кп (Fe360-A)	175 – 230		100 – 140
Steel grade ВСт3пс (Fe360-B)	230 – 280		140 – 170
Steel grade 09Г2	290 – 360		180 – 215
Concrete	0,26 – 1,68	2,14 – 33,6	–
Gray iron	55 – 100	160 – 250	40 – 75
Thermal strengthened aluminum alloys	125 – 200		75 – 100

Results of fireproof laminated glass strength measurements show that breakage load increases when total thickness and complexity of the composite sample increases. Ultimate strength in tables 2.1 and 2.2 was calculated according to the following formula from STP 12-5-78:

$$\sigma_i = 0{,}426\,\frac{P}{h_i^2}$$

where σ_i is strength (also ultimate stress or breakage stress) in centrosymmetrical bending of *i*-th sample, kg-force/mm^2; P_i - fracture load of *i*-th sample, kg-f; h_i - thickness of *i*-th sample, mm. So increasing of breakage load not necessary causes increase of the strength. Moreover, we see that strength characteristics could decrease in more complex samples.

In the obtained results we can't find any dependence of variation coefficient of the ultimate strength from structural complexity of the sample.

It could be noted that unsymmetrical constructions sustain greater loads when force applies to the glass side than to laminated glass side (Figure 1). This regularity confirmed both in calculations of average strength (Figure 1*) and ultimate strength with 0.1% probability of the failure (Figure 1**). Producers agreed with this conclusion and recommend installing such glasses with glass-side faces the possible mechanical treads.

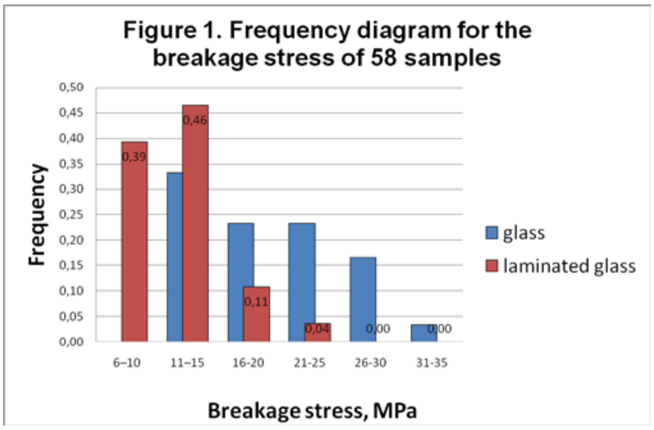

Figure 1. Frequency diagram for the breakage stress of 58 samples

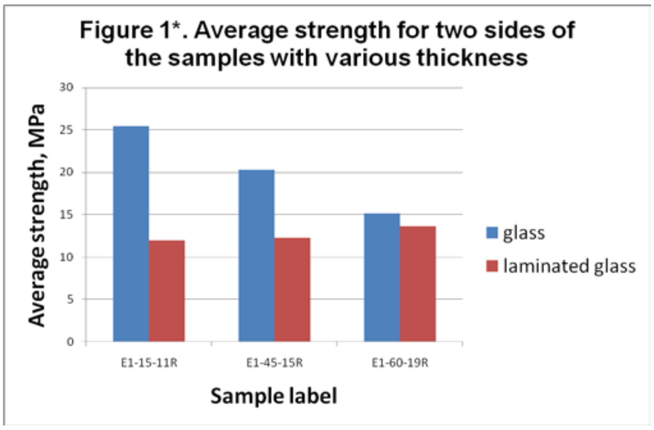

Figure 1*. Average strength for two sides of the samples with various thickness

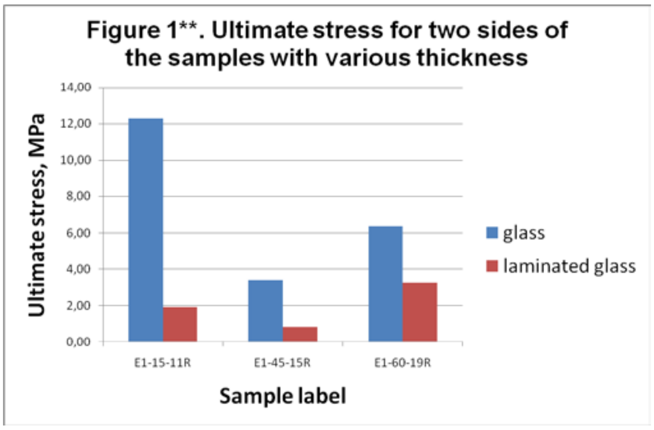

Figure 1**. Ultimate stress for two sides of the samples with various thickness

And it should be noted that when number of layers in the sample increases, disparity in ultimate strength of the different sides of glass under applied load decreases (Figure 1*).

Results of the tests show that average strength of the fireproof glass exceeds design strength of annealed glass but it is lower than design strength of the tempered glass products.

Comparison of results for initial reference float glass and ion-exchange toughened glass arrives to conclusion that such method of chemical strengthening brings to considerable increase of glass strength (up to 4 – 8 times). The main strength increment achieves during starting phase of the process (up to 2 hours) (in Figure 2 it can be seen as a big jump in average strength after 2 hours of treatment). Subsequent process phases (up to 16 hours of treatment) brings to substantially more uniform mechanical properties in the processed batch (in

Figure 2* - variation coefficient decreases), particularly if we take into account numbers for both sides of the samples. Difference between characteristics of tin and tinless sides also decreases, that could be reason for longer strengthening process.

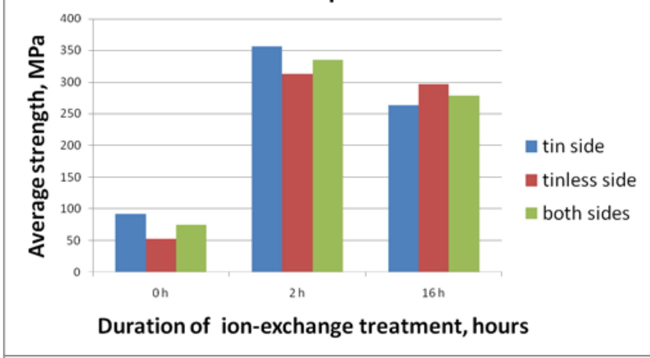

Figure 2. Ion-exchange process, 4 mm samples

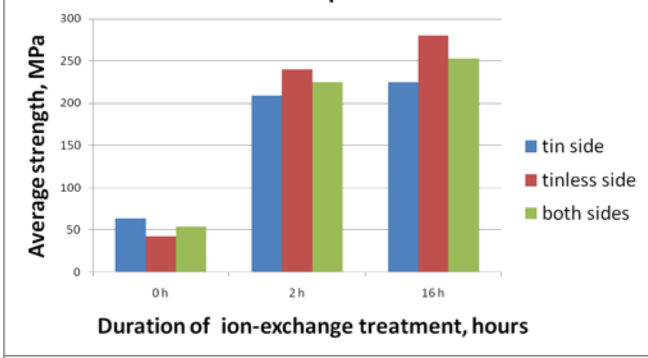

Figure 2. Ion-exchange process, 6 mm samples

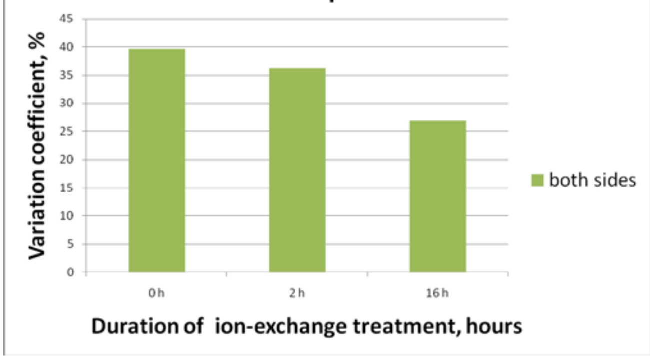

Figure 2*. Ion-exchange process, 4 mm samples

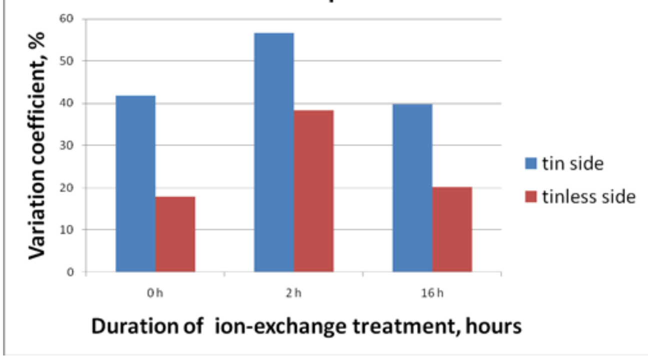

Figure 2*. Ion-exchange process, 6 mm samples

Variation coefficient of the ultimate strength in 4 mm thick glass samples batch decreased from 39.63% to 26.85% in total. For 6 mm thick glass it decreased from 41.3% to 31.02%. But this type of the treatment reacts non-equally on the opposite sides of the sample (See Table 2.2 as well).

5. Conclusions

Glass is an amorphous and brittle material and its characteristics spread are higher than for traditional construction materials. That fact requires continuing research of technological parameters and glass properties effecting to strength.

We did not find during this study any dependence between breakage stress in glass and visual appearance defects presence. There are some theories about strength during glass operation that predicts equalization of strength because of surface defects with considerable strength decreasing in the same time. But we can't support or disprove them now on the basis of our research.

Complex and non-uniform glass samples have substantially different strength when force applies to opposite sides of the plate. This fact should be taken into account in application of glass as construction material.

Chemical strengthening by ion-exchange process allows increasing strength properties and decreasing uncertainty in the batch, but works on the opposite sides of the sample in different way. It seems that tinless side of the glass reacts better and can stand higher fracture force after 16 hours treatment.

Because of glass strength problem topicality, it is necessary to continue theoretical and experimental research in this field.

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