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Assessment and Management of Strength and Durability of Composite Glass Elements

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The composite load bearing glass elements have the many advantages as compared with the massive glass structures [1, 2]. The use of high strength, plasticity or viscous behavior of the additional structural elements increases the safety and strength of glass composite. However, the main peculiarities of glass composite mechanical deforming, strength and fracture are remain induced by the primary influence of elastic and brittle nature of glass components on the whole composite structural behavior [1]. The technical approach for the assessment and management of the strength and durability of composite glass elements was developed basing on this position. The management of glass composite strength foresees the use some control tests of the mechanical state of glass components in the composite together with the specific constructional and technological solutions for strength increasing and maintenance in different service conditions [1-5]. Some results of the assessment and management of quality, strength and life time of the annealed and strengthened glass elements as the components of composites with increased carrying capacity are discussed in a paper.

Keywords: Glass, Composite, Quality, Structural strength, Durability

1. Introduction

The composite load bearing glass elements have the many advantages as compared with massive glass structures [1, 2]. Strong waterproof shells for pressure-operated marine housings made of sheet glass or pressed glassware elements (figure 1), illuminators and aircraft windshields as well as carrying building glass structures like stairs, multilayer plates and columns are the composite units.

The composite cylindrical section assembled of sheet glass rings (on the left) and hybrid glass-metal shell made of the pressed glass sections with aluminum rigs and steel flanges (on the right) are shown in the figure 1. These shells made using the adhesive joints were tested under external pressure in the range 40…78 MPa [1] and 30 MPa, correspondingly. High level of the specific compression strength, transparency and other positive structural properties of glass are supplement with the properties of structural materials of the additional structure components. In the result of that, the failure compression stress for composite glass section showed in the figure 1(on the left) was in diapason 660…860 MPa under single and multiple tests in high pressure chamber. It was shown that maximal values of the operation pressure for these types of shells may be in the range 40…60 MPa under the short time and durable loading. The experimental values of the compression strength up to 1000…2000 MPa were obtained under the axial and biaxial compression as well as under external pressure tests of the composite glass elements made of sheet glass components [1]. The experience of developing of marine pressure glass shells based on the use of high compression strength of glass under appropriate conditions may be useful for other sphere of technique. We think that exposed reserves of compression strength of a glass may by used in the building and engineering industry to make the load bearing glass structures more effective.

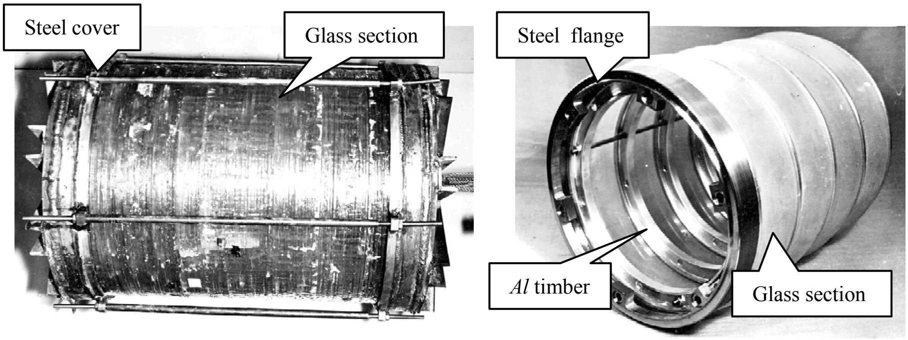

Figure 1. Strong composite glass shells intended for high external pressure.

The use of high tensile strength, plasticity or viscous behavior of the additional reinforcing components may change the mechanical behavior of glass composites and enable to increase their safety and strength. However, the main peculiarities of their mechanical deforming, strength and fracture are stay induced by primary influence of elastic and brittle nature of glass components on the limiting state and whole composite structural behavior under the operating loads [1,2]. The multilayer bulletproof glass and composite rings made of sheet glass components for strong shells are shown in the figure 2. It is obvious that the fracture of bulletproof glass as well as of composite rings placed to the fore in the photo depends mainly on the quality and strength level of glass components.

Some important design features are character for the glass composite structures. The volume content of carrying glass components reaches 90…95 % that is significantly higher than in other traditional fibrous and laminate composite materials. These components have the solid or large-sized block constructions. Their characteristic dimensions such as the thickness are by order of magnitude greater than sizes of adhesion and reinforcing components made of other constructional materials. It is shown in the figure 2 that the whole of composite construction may be fractured or damaged irreparably in the case of the fracture even of one of the glass layers. A small local surface damage and more significant fracture of the glass components in the result of contact with rigid body or inadequate strength of glass component may be cause of the bearing degradation of the composite unit as a whole.

Figure 2. The multilayer bulletproof glass and composite rings made of sheet glass components.

The technical approach discussed in this paper stipulates the assessment and management of the strength and durability of the glass composite elements basing on the idea of the specific primary influence of glass components on the load bearing behavior of glass composites. Than more strong and durable are the glass components than higher may be the carrying capacity of composite glass structures. The management of glass composite strength foresees the use some control tests of the mechanical state of glass components in the composite together with the specific constructional and technological solutions for strength increasing and maintenance in different service conditions [1-5]. Some results of the assessment and management of quality, strength and life time of the annealed and strengthened glass elements as the components of composites with increased carrying capacity are discussed in a paper.

2. Strength of glass components and load bearing behavior of glass composites

The load bearing behavior of the advanced glass composites differs significantly from the solid glass and usual triplex behavior under the mechanical loading. The deformation curves of some reinforced glass composites under 3-point bending are shown in the figure 3. The length of specimens was 150 mm, width - 25 mm and span – 115 mm. Specimens were tested on an “Instron-1126” testing machine. Test speed of 1 mm/min was used. There are curves for a triplex made of 5 mm annealed glass with

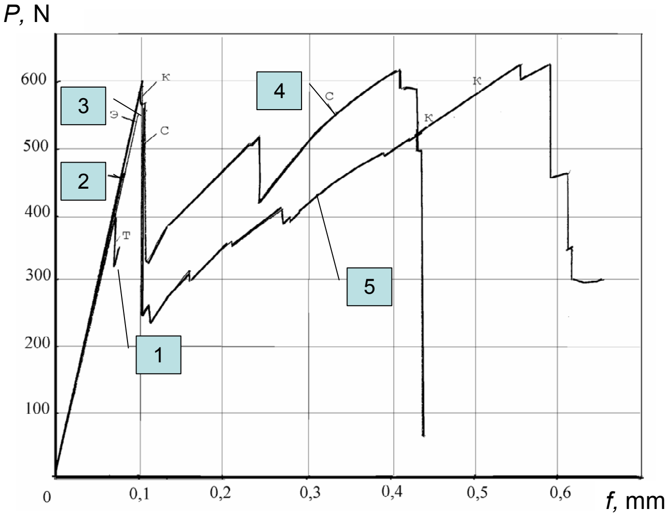

Figure 3. Deformation curves of the reinforced laminated glass composites under the bending. (The data were received together with Dr. Zemtzov M.P. and Dr. Skripchenko V.I.)
1 – triplex 5 -0.37-5 mm (PVB); 2 - reinforced triplex (epoxy resin with boron fibers); 3 - reinforced triplex (epoxy covering); 4 - reinforced triplex (epoxy resin with steel wire); 5 - reinforced triplex (epoxy resin with Kevlar).

a PVB film 0.37 mm (curve 1) and the same triplex reinforced in a variety of ways using the reinforcing covering on the tensile surface. The reinforcements were applied on tensile surface of the bottom glass layer. The boron and Kevlar fibers as well as steel wires were directed along the axis of specimens and coated with epoxy resin layer about 1.6 mm in thickness. The curves 2 and 3 for triplex with epoxy boron and epoxy covering are similar to usual linear deformation curves for monolithic and laminated glass (curve 1). It is obvious that practically the same angle of slope is character for these curves as well as for the curves 4 and 5 (reinforced triplex with the steel wires and Kevlar) on the first stage of composite deforming that is finishing at the destruction point of lower glass layer in tension. The values of the modulus of elasticity of glass, bending stiffness of glass layers as well as the strength and life time of glass are of primary importance until the glass component fracture beginning. The influence of reinforcing components like boron epoxy covering and other kinds of reinforcement is shown in the increasing of failure stress and changing of overcritical behavior of the laminated composite structures into safer mode. The failure load of composite specimens was increased from 400N to 600 N in the result of reinforcement of a triplex.

The fracture character of the tested composite glass specimens is shown in the figure 4.

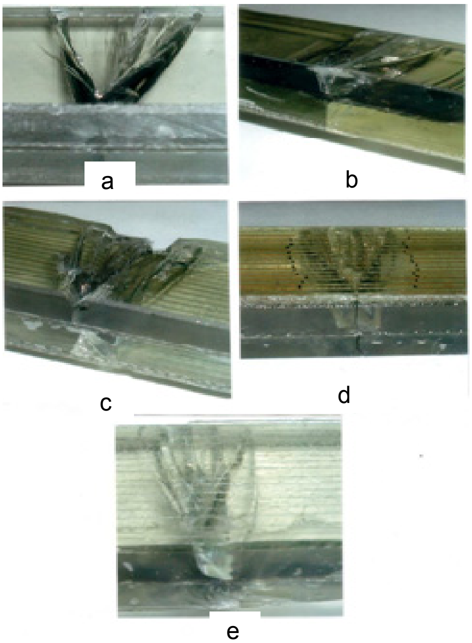

Figure 4. The character of specimen fracture of the reinforced triplex
a – basic triplex; b – triplex with epoxy covering; c – triplex with boron fibers;
d – triplex with steel wires; e – triplex with Kevlar.

The edge microcracks in the tensile surface of glass component are the fracture source in all tested composite structures. The brittle modes of failure are characteristic for reinforced composites. These fracture modes depends on the glass components mechanical state mainly. The significant load drop mentioned in the curves 3, 4 and 5 on the figure 3 after the first stage of composite fracture at the deflection $f = 0.1$ mm is the result of crack instability and large area of fractured region of glass components. The second glass layer fractured at this time also. The load bearing behavior of tested glass composites may be more stable at the overcritical stage of the structural element loading if the volume fraction of reinforcing components will be increased significantly and their adhesion bonds with glass fragments after glass layer fracture will be strong enough.

Therefore, the increasing of the glass component strength is an important way of carrying capacity and durability of structural composite glass elements. The other challenging direction may be connected with the use of compressed glass elements as the high strength components of composite and integrated structures.

The results of an experimental study of glass compression strength under durable contact loading are presented in the figure 5 [6]. The glass bars were tested under axial compression between the flat steel plates without the space filler. The mean value of strength at the 10 minutes time of a loading was about 750 MPa. Long-term compression strength decreased up to 500 MPa. Minimal values of the contact strength of glass specimens under compression changed slowly. The minimal values for long-term loading were about the 400 MPa. This is in 10 times higher than tensile and bending strength of the glass. These results show that high strength joints and many other technical solutions developed for pressure shells may be used effectively in some compression-operated building structures.

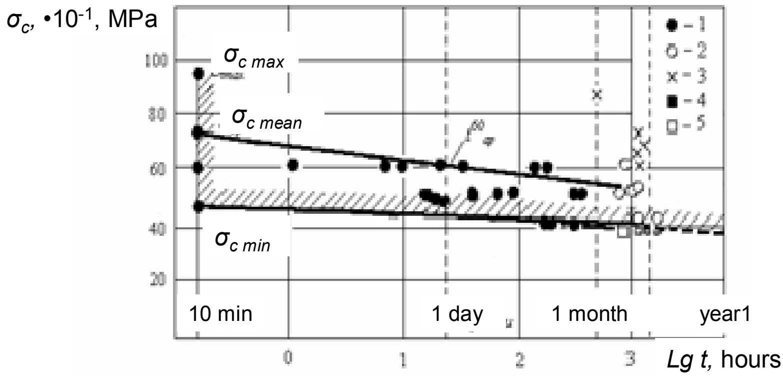

Figure 5. Durability curves for glass bars under contact axial compression.

This direction of the use the structural compressive strength of glass in the building was demonstrated in the projects of the frameless glass dome [7], composite block structure of the 11 March Memorial in Madrid [8] and in the concept of transparent space grid structures made of steel glass modules pursues the use of compressed glass layer as part of the primary load-bearing system [9]. The rough assessment of average compression stress in the glass composite block structure made from borosilicate glass [8] gives the value about 0.25…0.3 MPa. This is more than three order of decrease against to minimal value of long-term compression strength shown in the figure 5. Therefore, significant reserves of glass compression strength may be used more effectively for architectural design of building glass structures.

3. Assessment and management of glass component strength and durability

Strength and durability of glass are the parameters dependent on processing quality, factual state the glass surface and effectiveness of the technology of strengthening [1, 3-5]. So the problems of strength and durability assessment of composite glass carrying structure must be solved on the basis of data on factual mechanical state of glass components in the composite [10].

Strong laminated and other carrying composite glass structures based on the thermally hardened glass elements have a wide sphere of using in modern architecture [3]. But their factual bending strength and durability assessment are characterized by high level uncertainty in spite of the existing of special building norms [3, 10-13]. In contrast to annealed glass some additional factors have the significant influence on heat strengthened (HS-glass) and fully tempered (FT-glass) glass element mechanical behavior. Two main components determine the strength level of thermally strengthened glass σ_{ts} as it may be illustrated by the equation:

$$\sigma_{ts} = \sigma_{fs} + \sigma_{I\,rs} \tag{1}$$

First component σ_{fs} is the fracture strength of glass surface or "pure" glass surface strength concerned with state of surface microcracks and kinds of stress induced by external loads. It is considered usually that fracture strength of glass surface is equal to initial strength of annealed glass [11,13]. But factual data on fracture strength of toughened glass surface verified by measurement to understand the impact of oven units and production standards are absent. The residual surface compression stress σ_{rs} imposed by the toughening process is the second component of hardened glass strength. True level of surface compression stress located near the concrete fracture source is unknown. But it must be determined exactly for the assessment of hardened glass element strength. Standard optical measurements made according to EN 12150-2:2004, point B.1.2. give not answer on that question. In tote the relevant changing of glass surface defectiveness as well as the real parameters of residual surface compressive stress and their actual influence taking place under the heat treatment of structural elements are studied not enough. Thus, the prediction of hardened glass element strength subject to factual contribution of both these mentioned components - σ_{fs} and σ_{rs} is now the complicated actual problem of glass tempering and building structure design.

The quality of toughening glass technology plays the leading hand in this problem solving. Last detailed experimental results showed particularly that parameters of statistical distribution for bending strength of HS- and FT-glass plates may depend on quality of glass edge mechanical treatment and tempering in many different ways under influence of residual stress and various loading conditions [3]. That is why the optimization of glass tempering technology using the experimental data on strength and fracture parameters of glassware may be important instrument to guarantee the durability of architectural carrying glass structures. The objective of the research was to assess the real influence of surface defectiveness, glass fracture resistance and residual stress on carrying capacity of heat strengthened and fully tempered glass plates under the bending. It was important task to show that whole of glass toughening technology determines fully the basic components of hardened glass strength.

Special and standard specimens made of annealed and fully tempered clear float glass with the thickness h = 4…12 mm were used in the study:

- «standard» 1100 x 350 x h; area of 3500 cm^2
- «½ of standard » 600 x 300 x h; area of 1960 cm^2
- «¼ of standard» 300 x 300 x h. area of 810 cm^2

Specimens were made on the production line based on the oven "Tamglass" HTF-ProE 2136. The parameters of specimen bending test on 4 –point scheme (distances between lower and upper supports – L and l, ratio l/L and area of test portion F_{tp}) are given in the Table 1.

Some specimens were tested with parameters given in brackets to estimate the influence of loading scheme on test results. It was shown that results received under the different scheme of loading were approximate to similar for specimens with the same thickness and they were similar for all three types of specimen's sizes. The edges of specimens were grinded and polished using the common operating practices for building glass elements.

Table 1. Data on specimen series for bending tests of annealed and tempered glass.

Sizes, mm	L, mm	l, mm	l/L	F_{tp}, cm^2
1100 x 350	100	200 (670)	0.2 (0.67)	700 (2345)
600 x 300	560	200 (300)	0.36 (0.54)	600 (900)
300 x 300	270	130	0.48	390

Hydraulic mechanical testing machines ZD-4 and ZD-40 were used. The rate of bending stress increase was in the range 0.2…2 MPa/sec subject to specimen flexibility concerning with scheme of specimen loading. Special microfractography method was used to study the depth and other geometrical parameters of surface microcracks – fracture sources in the fractured annealed and tempered glass specimens [5,11]. It were determined the limiting microcrack parameters which are characteristic for critical stage 1 of stable crack growth under the bending.

Basing on these experimental data and linear fracture mechanics we calculated the fracture strength of glass surface - σ_{fs} using the equation:

$$\sigma_{fs} = K_{I\,cr} / Y_1 \sqrt{b_1} \tag{2}$$

where K_{cr} - critical stress intensity factor; it was assumed according to our experimental results that K_{cr}= 0.5 MPa√m for this glass; b_1 – experimental limiting values of depth b_1 of semi elliptical microcrack in fracture focus of crack growth and fracture surface pattern formation; Y_1 - geometrical parameter of microcrack in fracture focus calculated basing on the experimental values of a ratio b_1/A_1 at the critical stage 1 of crack growth and on the appropriate equations of fracture mechanics; A_1- length of microcrack measured along the surface for the critical stage 1. The factual level of local residual compressive stress near the fracture source in tempered glass element was assessed using the calculated value of component σ_{fs} on equation:

$$\sigma_{rs} = \sigma_{ts} - \sigma_{fs} \tag{3}$$

Therefore, general solution for forecasting of the thermally strengthened glass element strength under the bending may be shown by the equation:

$$\sigma_{ts} = \sigma_{rs} + K_{I\,cr} / Y_1 \sqrt{b_1} \tag{4}$$

The results of our tests were analyzed and compared with known fundamental data on HS- and FT-glass received for 15 different lines [13] and other results [3, 5]. Some data on the bending strength of annealed glass received for different glass state and using the various specimens are shown in the figure 6. The specimens made of freshly made glass sheets were tested. Some specimens were stored 4 years in laboratory conditions before the testing. There were used in addition some data on annealed glass strength of the other authors [3,14]. The decreasing of annealed glass strength when the thickness of glass rises is a main tendency. Long-term storage of unpacked ware and rough handling are not acceptable for strong hardened glass production owing to an additional glass damaging. Low initial quality of glass and insufficient grade of glass element edge mechanical treatment in case of badly arranged quality control at the glass processing are the reasons of lower mean values and very low minimal level of bending strength – up to 25…30 MPa. This was shown convincingly in the statistically validated tests [3].

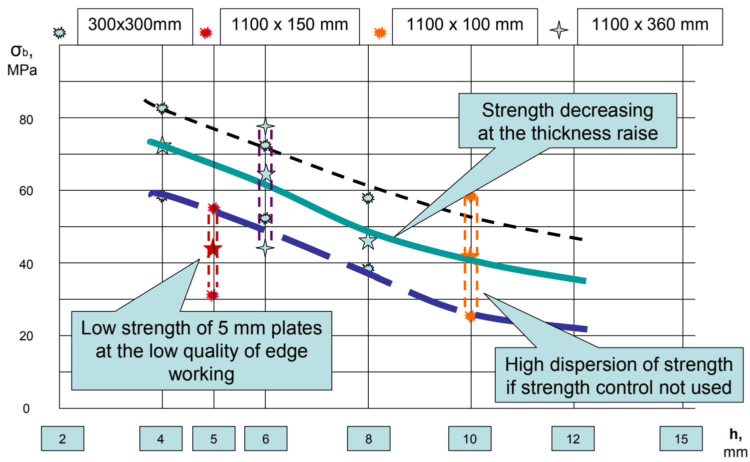

Figure 6. Quality and bending strength σ_b of annealed glass subject to thickness of the plates.

Figure 7 shows that fracture surface strength σ_{fs} calculated basing on equation (2) and fracture analysis results for tempered glass plates is lower than initial strength of annealed glass σ_b. This is a result of the additional growth of the biggest surface microcracks under the influence of heat treatment and contact conditions at the interaction with hard elements of tempering line equipment. It was shown also that depth of biggest surface microcracks may increase about three – five times more than initial depth under the usual tempering conditions. As the result of that the fracture surface strength for tempered glass decreases and lower boundary of the values of σ_{fs} weakly changes from 30 MPa for 4 mm glass to 20 MPa for 12 mm glass.

Thus, it is not desirable to use the assessment of thermally strengthened glass element strength σ_{ts} basing on initial annealed glass σ_b test results. In compliance with equation (1) the factual strength of HS- and FT-glass element may differ significantly depending on quality of tempering process and effectiveness of glassware surface state control used in the real production practice.

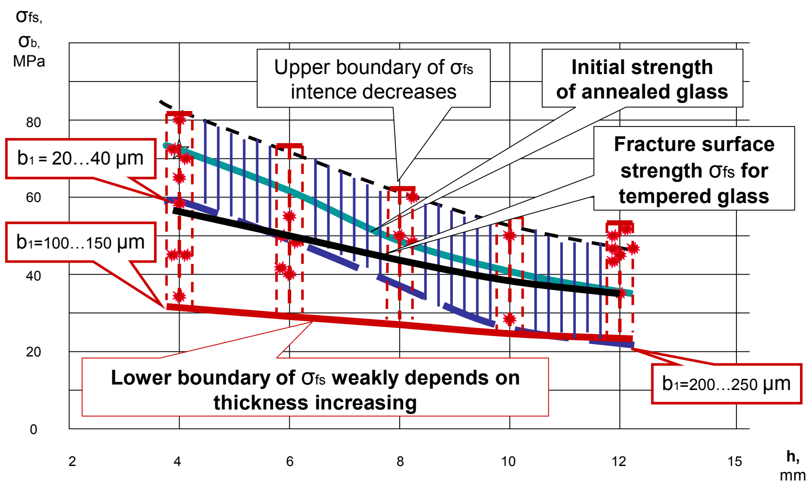

Figure 7 Influence of glass thickness on decreasing of glass surface mechanical resistance under the tempering conditions.

Figure 8 shows the experimental bending strength results for FT-glass σ_{ts} and small influence of hardened glass fracture surface strength σ_{fs} on their changing depending on different glass thickness. The residual stress level influences mainly on fully tempered glass bending strength. Mode of thickness dependency for tempered specimen strength not correlates with the curve shape for fracture surface strength of hardened glass. Lower boundary of the tempered specimen strength σ_{ts} values rises to 160…180 MPa for enlarged thickness of glass whereas glass surface mechanical resistance σ_{fs} decreases of up to 20…30 MPa because the level of residual stress is significantly higher than fracture surface resistance.

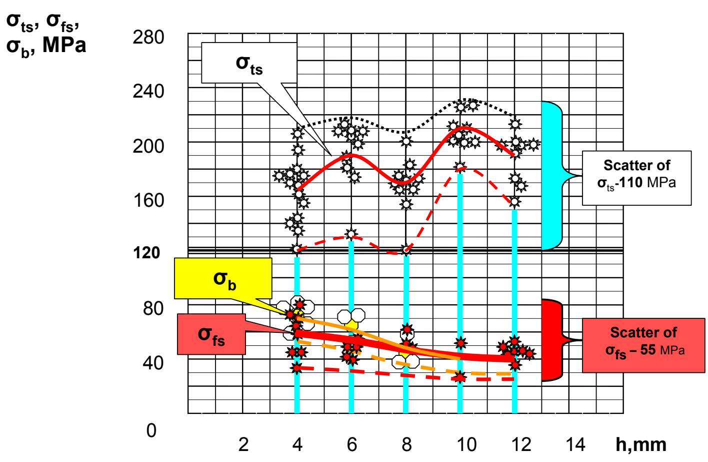

Figure 8. Fracture surface strength σ_{fs} and bending strength σ_b of tempered glass.

It was shown that influence of thermal strengthening on strength of hardened glass with different thickness is depending first of all on the level of residual surface compressing stress connected directly with the stress tempering quality and concrete operating mode (Figure 9). The redundant factual level of σ_{rs} (up to 180 MPa instead of the normal 80... 110 MPa) and high scatter of this stress (up to 110 MPa) are the causes of supernormal bending strength and large standard deviation of tested tempered glass and of the results [13]. The more it is residual compressive stress the more is hardened glass strength.
The results of durable bending tests of EN specimens and plates of tempered 4 and 6 mm glass 2.5 x 0.5 m have showed the possibility to increase the long-term operation stress up to 80…100 MPa if high quality of glass elements will be guaranteed on the production line.

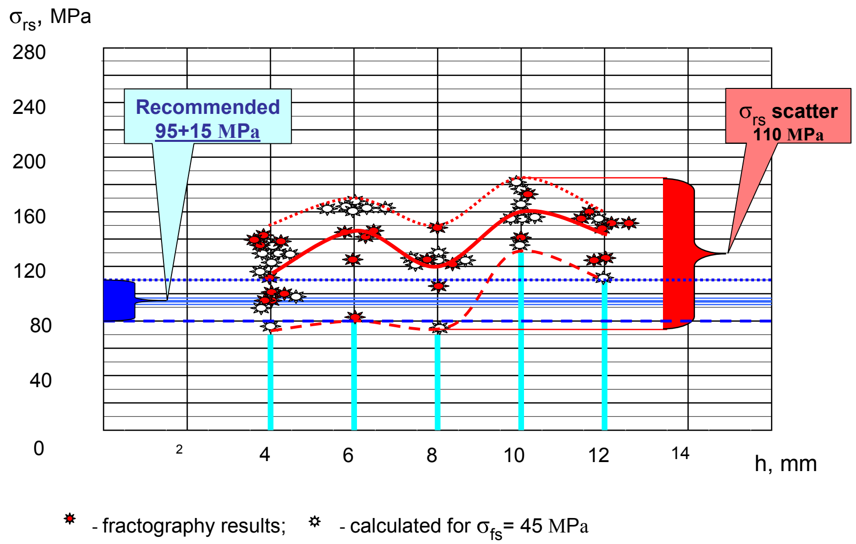

Figure 9 Residual compressive stress and quality of the hardened glass.

4. Summary

The technical approach for the assessment and management of the strength and durability of composite glass elements based on the primary influence of elastic and brittle nature of glass components on the whole composite structural behavior was developed. The management of glass composite strength foresees the use some control tests of the mechanical state of glass components in the composite together with the specific constructional and technological solutions for strength increasing and maintenance in different service conditions.

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6. References

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