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STRENGTH STUDY ON SODA-LIME-SILICATE-TOUGHENED GLASS

ABSTRACT

Toughened soda-lime-silicate glass is a popular material widely used in construction due to its very good functional properties, characterized by its high strength, safety in use, fire resistance, and good thermal insulation. In this study, tests were conducted to describe the dependence between the bending strength of ESG-toughened float glass and the thickness of the sample, state of the sample edge, and application of security film. Tests were also conducted on the influence of the placement of openings needed for mounting glass screens used to secure display cases and other objects of a similar nature. The information obtained was used to design glass security screens and a new type of display case, a closed cassette with a glass screen intended for use in protecting works of art from acts of vandalism and the destructive influence of environmental conditions.

Keywords: *toughened soda-lime-silicate glass, bending strength, security film*

BADANIA WYTRZYMAŁOŚCIOWE HARTOWANEGO SZKŁA SODOWO-WAPNIOWO-KRZEMIANOWEGO

Szkło hartowane sodowo-wapniowo-krzemianowe jest popularnym materiałem stosowanym powszechnie w budownictwie, ze względu na bardzo dobre własności użytkowe charakteryzujące się wysokimi parametrami wytrzymałościowymi, bezpieczeństwem eksploatacji, ognioodpornością, jak również dobrą izolacyjnością termiczną. W pracy wykonano badania mające na celu określenie zależności wytrzymałości na zginanie szkła hartowanego float ESG od grubości próbki, stanu obrzeża próbki oraz zastosowania folii antywłamaniowej. Wykonano również badania wytrzymałościowe wpływu rozmieszczenia otworów zamocowania ekranów szklanych stosowanych do zabezpieczania obiektów wystawienniczych na ich wytrzymałość. Uzyskane informacje wykorzystane zostały przy projektowaniu przeszkleń ochronnych oraz nowego układu gablota – zamknięta kaseta z przeszkleniem szybą, służących jako zabezpieczenie dzieł sztuki przed wandalizmem i oddziaływaniem niekorzystnych warunków środowiskowych.

Słowa kluczowe: *szkło hartowane sodowo-wapniowo-krzemianowe, wytrzymałość na zginanie, folia antywłamaniowa*

1. INTRODUCTION

One of the most commonly used materials in building is toughened soda-lime-silicate glass, a material whose functional properties are significantly improved as a result of tempering and applying safety coatings such as security film. This material is characterized by a high level of safety in use, as a result of its resistance to sudden changes in temperature across a wide range, resistance to stresses from high winds, snow, noise, fire, fixed and variable loads, attempts at break-ins (including impacts from blunt objects and projectiles), as well as explosions. This type of glass also simultaneously exhibits very good thermal insulation properties, and when used in conjunction with appropriate protective film coatings, it also considerably reduces the influence of harmful UV radiation. This also helps increase its strength, resulting in increased safety, as a result of the reduced risk of the glass falling out of its frame.

Because one of the basic strength properties of toughened glass is its resistance to breakage due to bending (PN-EN 12150-1), a series of bending strength tests were conducted in this study on samples of glass of various thickness, with various types of edge finishing, as well as with the additional application of security films in order to define the influence of these factors on the bending strength of the toughened soda-lime-silicate glass. Tests were also conducted on the influence of the placement of openings used for mounting glass screens on the strength of these screens.

2. BENDING STRENGTH TESTS

Bending strength tests were conducted in accordance with the requirements of the norm PN-82/B-13151. In these tests, 100 mm × 300 mm samples made of ESG float glass (soda-lime-silicate) were used (PN-EN 572-1, PN-EN 572-2). The tests were conducted for samples of various thickness (5, 6, 8, and 10 mm) whose edges were finished after cutting and before tempering according to the norm PN-EN 12150-2; for various sets of samples these edges were arrissed, smooth ground, and polished in accordance with the requirements of the norm PN-82/B-1315 (Fig. 1).

Each sample was marked on the side on which cutting took place. In the tests, Safety MIL security film with thicknesses of 0.11 and 0.22 mm was used. Bending strength tests of the samples with security film were conducted three weeks after the application of the film.

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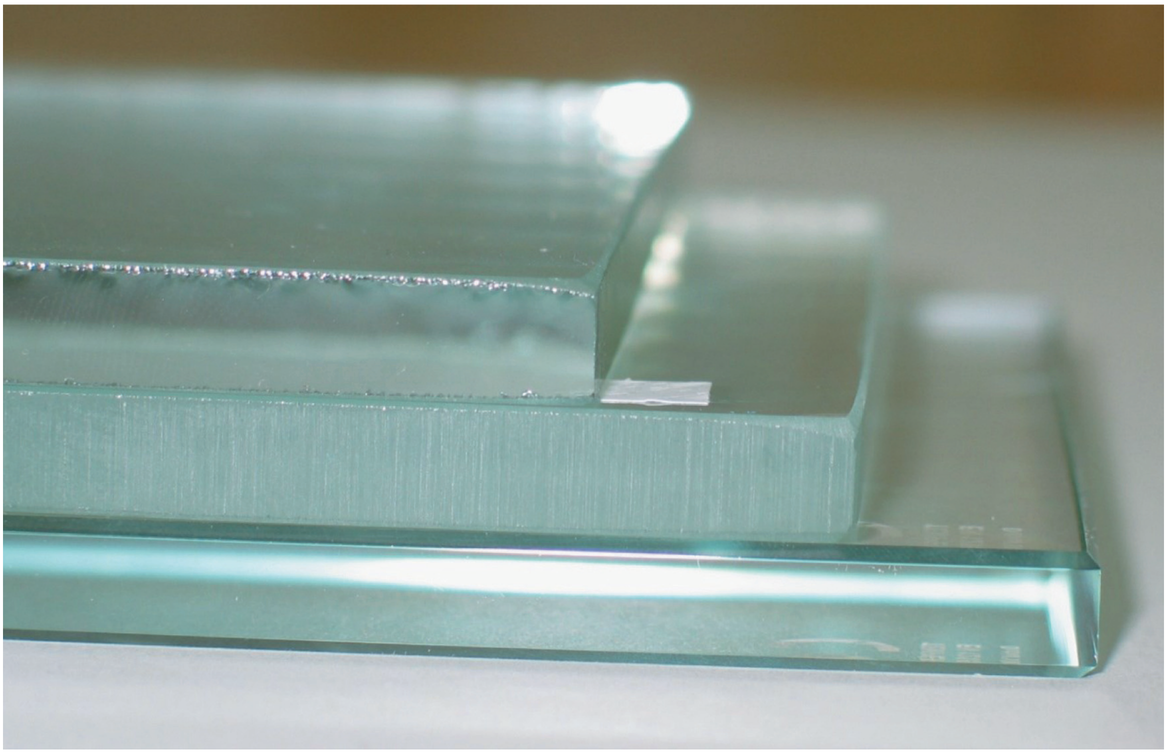

Fig. 1. Condition of sample edges from top to bottom: arrissed, smooth ground, and polished

Tests were conducted in total for 10 sets (with 14 samples in each set) with the following specifications:

- four sets of samples with thicknesses of 5, 6, 8, and 10 mm with arrissed edges,
- two sets of samples with thicknesses of 5 and 8 mm with smooth ground edges,
- a set of samples with a thickness of 8 mm with polished edges,
- a set of samples with a thickness of 8 mm with smooth ground edges and security film with a thickness of 0.11 mm,
- a set of samples with a thickness of 8 mm with smooth ground edges and security film with a thickness of 0.22 mm,
- a set of samples with a thickness of 8 mm with polished edges and security film with a thickness of 0.22 mm.

Support elements consisting of two polished steel cylinders with a diameter of ϕ30 mm and length of 120 mm were used (which were coated with a thick grease layer in their bearing sets to decrease friction during the test). The samples were placed on the testing station so that the axes of the samples lined up with the transversal and longitudinal axes of symmetry of the load system.

Stresses in a three-point transversal bending test were defined by the following formula:

$$\sigma = \frac{M_g}{W_g} = \frac{PL \cdot 6}{4 \cdot bh^2} = \frac{3PL}{2bh^2} \tag{1}$$

where:

M_g – the extreme bending moment value, $M_g = PL/4$,
W_g – the bending strength index of the rectangular cross-section, $W_g = bh^2/6$,
P – the breaking force of the sample,
L – the span between the support points of the sample, $L = 50$ mm,
b – the width of the sample,
h – the thickness of the sample.

Tests were conducted on a ZD10 tensile testing device, with a measurement range of 0–100 kN. The increment of increase in stress was assumed as a steady 70 MPa/min. The samples were placed on the testing station, so that scratches arising during cutting were always located at the bottom (that is, on the support side). In the case of samples with security film that was applied from the cut surface of the sample, the samples were placed on the testing station with the film side at the bottom (that is, on the support side). The testing station for conducting the bending strength tests on the samples with security film is illustrated in Figure 2. In no cases did the tests conducted on the samples with film indicate the occurrence of breakage of the film nor peeling of the film from larger shards of glass.

Fig. 2. Studies on transversal bending strength for 8 mm-thick glass samples with polished edge and 0.22 mm security film

3. RESULTS OF BENDING STRENGTH TESTS ON GLASS SAMPLES

The results of transversal bending strength tests for the nine sets of samples under consideration are shown in Table 1 (Ładecki 2011), in which the average breaking forces obtained and bending strength are collated together with standard deviations and variability factors. The dependence of bending strength on the thickness of the sample for the sets under consideration is illustrated in Figure 3.

Table 1

Results of transversal bending strength tests (Ładecki 2011)

Sample thickness, mm	State of sample edge	Breaking force P_{av}, kN	Bending strength σ, MPa	Standard deviation *S*, MPa	Variability factor *V*, %
5	arrissed	5.77	184.3	20.2	11.0
	smooth ground	5.65	178.7	25.4	14.2
6	arrissed	8.53	186.5	24.1	13.0
8	arrissed	13.1	162.1	33.4	20.6
	smooth ground	12.3	151.6	21.0	13.8
	polished	13.8	171.4	25.5	14.9
	smooth ground + film 0.11 mm	15.0	184.5	17.8	9.6
	smooth ground + film 0.22 mm	15.6	193.3	19.2	9.8
	polished + film 0.22 mm	17.2	209.7	30.3	14.3
10	arrissed	25.1	197.0	25.2	12.8

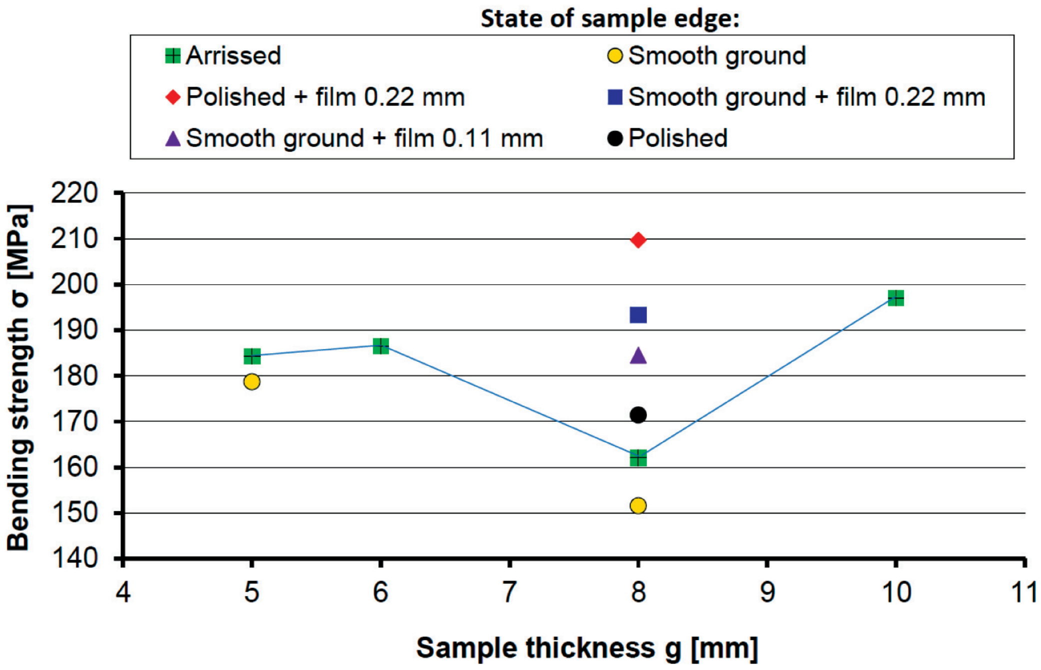

Fig. 3. Dependence of bending strength on thickness, state of the sample edge, and application of security films of different thicknesses

An analysis of the bending strength test results presented in Table 1 and Figure 3 shows that, in each case, this bending strength is higher than the minimum bending strength required by the PN-EN 12150-1 norm (120 MPa). For the four sets of samples with arrissed edges, an increase in thickness was associated with an increase in bending strength; disregarding the samples with a thickness of 8 mm, this increase is approximately linear. For the set of samples with a thickness of 8 mm, there is a noticeable decrease in bending strength of more than 11% from the linear progression, which can most likely be explained as the result of technological factors in the manufacturing and toughening processes of the glass used for this set of samples.

In the tests conducted for two sets of samples with thicknesses of 5 and 8 mm with smooth ground edges, the samples were found to have decreased bending strength in comparison with the samples with arrissed edges, which contradicts the theory posited in (Korzynow 2006, Korzynow 2011), where it was claimed that the smoother the surface of the edge, the less risk exists of the appearance of cracks and Griffith fractures, which should increase the bending strength of the sample. In all probability, it is precisely during the grinding process that these types of cracks and fractures appear, which then reduce the bending strength of the glass; however, cheaper rough arrissed edges demonstrate greater smoothness than smooth ground edges (Dowling 1999, Machniewicz 2012) (Fig. 1). Tests conducted on the set of samples with a thickness of 8 mm with polished edges showed an increase in bending strength as compared with the samples with lower-quality edge finishing.

Tests conducted on three sets of samples with a thickness of 8 mm with smooth ground edges without security film and with the application of security film with thicknesses of 0.11 and 0.22 mm indicated an increase in bending strength of the samples with security film with a thickness of 0.11 mm of 21.7% as compared to the samples without film, while for the samples with security film of thickness 0.22 mm, the increase in bending strength in comparison to samples without foil amounted to 27.5%. The application of the thicker film (0.22 mm) to the samples with a thickness of 8 mm with polished edges gave the best results of all sets of samples across the full range of thicknesses.

Tests conducted for all sets of samples showed the occurrence of a disparate set of results. For different sets of samples, the standard deviation varied from 17.8 MPa to 33.4 MPa, whereas the variability factor was within a range of 9.6% to 20.6%.

4. TESTS ON THE INFLUENCE OF PLACEMENT OF OPENINGS USED FOR MOUNTING ON STRENGTH OF GLASS SCREENS

The basic guidelines for the placement of openings used for mounting the screens are outlined in the

PN-EN 12150-1 norm. The distance between the edge of the opening and the edge of the glass, and the distance between the edges of the neighbouring openings should be greater than 2*d* (where *d* is the diameter of the circular opening). An additional condition is applied, specifying that the distance of the edge of the opening from the edge of the glass screen may not exceed 6*d*. Taking the above into consideration, strength tests were conducted on glass screens with various configurations of the openings, all of which met the requirements of the norms.

Mechanical strength tests on glass screens mounted with spacer bolts aiming at discovering the optimum placement of the spacer bolts used to mount the screens were conducted on toughened ESG float glass screens with dimensions of 8 mm × 300 mm × 500 mm having openings with a diameter of $d = 11$ mm and placements of the openings (as in Figure 4) in the following configurations: $a = 40$ mm and $b = 70$ mm; $a = 22$ mm and $b = 70$ mm; and $a = 40$ mm and $b = 30$ mm.

Tests were conducted at a station consisting of a laminated particle board with dimensions of 40 mm × 410 mm × × 740 mm, to which glass screens with various configurations of the openings for mounting bolts were attached using FS2020IX type bolts. The bolts were screwed in with a torque of 1 Nm. The particle board was placed on a steel plate with a thickness of 20 mm, and the whole assembly was placed on the beam of a ZD10 tensile testing device. A steel element in the shape of a cut-out of a sphere with a diameter of ϕ98 mm was used as the impacting element to obtain a point load in the centre of gravity of the screen. A diagram of the load system is shown in Figure 5.

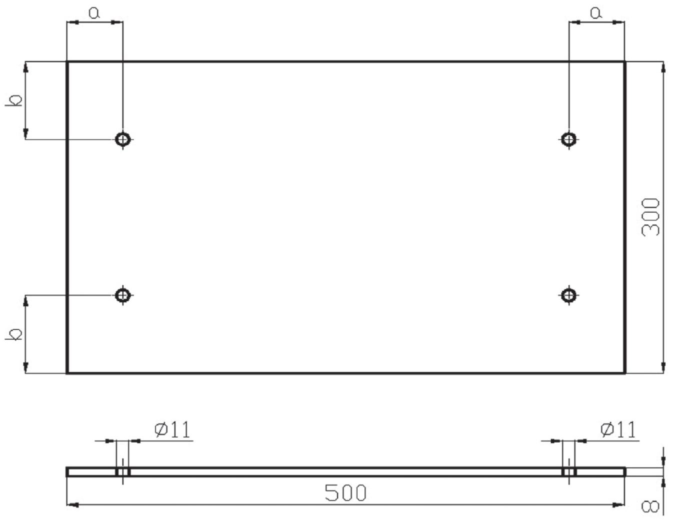

Fig. 4. Dimensions of glass screen

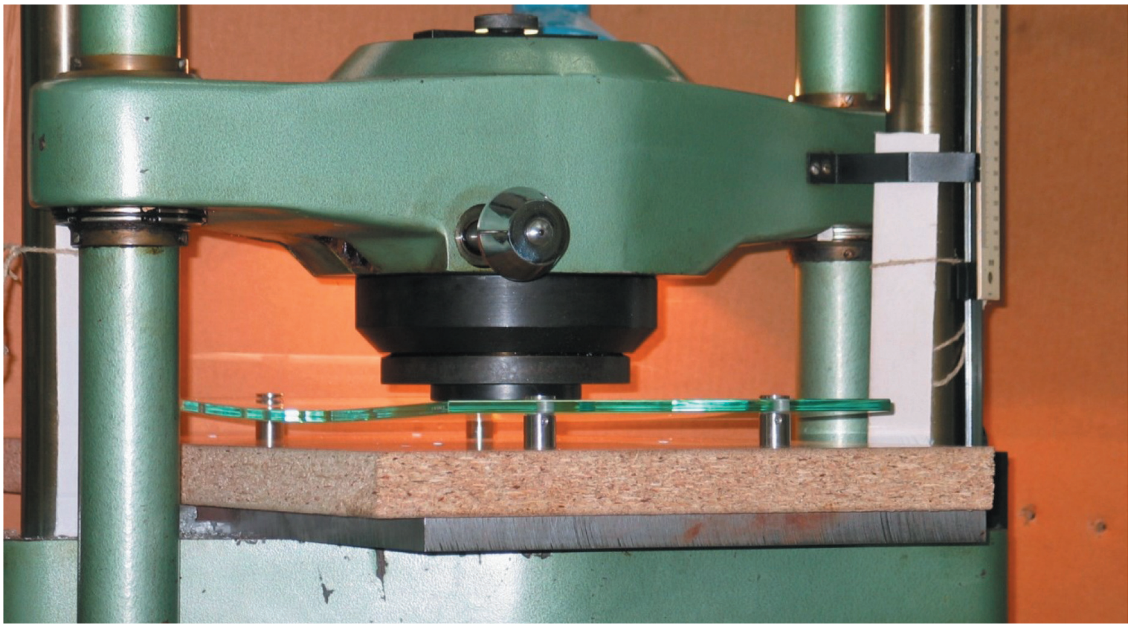

Fig. 5. Diagram of load system of glass screen

5. RESULTS OF TESTS ON GLASS SCREENS

Strength tests were conducted for a total of nine screens with smooth ground edges, three of each with the three different combinations of opening placement. The load increment amounted to 70 MPa/min. The results of the tests conducted are collated and presented in Table 2 (Ładecki 2011), in which the breaking forces for the glass screens are collected together with their relevant deflection curves at the moment of breakage. After the tests were conducted, no instances were observed of damage to the spacer bolts used in the mounting of the screens.

An analysis of the tests collated in Table 2 shows that, in the case of the openings placed at a distance of $b = 70$ mm from the longer edge of the screen, slightly more favorable results were obtained when these openings were placed further ($a = 40$ mm) from the shorter edge of the screen; however, in both cases ($a = 40$ mm and $a = 22$ mm), the difference in average breaking force was not great. When the openings were placed at a distance of $a = 40$ mm from the longer edge, reducing the b distance from 70 to 30 mm, caused a significant decrease in the average breaking force (exceeding 21.0%). Those tests that generated highly disparate results may be treated as preliminary studies.

Table 2

Results of strength tests on glass screens (Ładecki 2011)

Distance between openings, mm (as in Fig. 4)		**Breaking force P, kN / deflection Δl, mm**			
a	**b**	**Sample No.**			Average
		1	2	3	
40	70	5.96 / 10.8	4.97 / 9.3	4.71 / 8.8	**5.21** / 9.6
22	70	5.86 / 13.3	5.45 / 12.5	3.76 / 8.7	**5.02** / 11.5
40	30	2.99 / 5.8	5.52 / 9.9	4.40 / 8.3	**4.30** / 8.0

6. CONCLUSIONS

The tests conducted on bending strength of soda-lime-silicate-toughened glass showed that, for samples with an arrissed edge, the glass strength rose in an approximately linear fashion together with an increase in thickness (with the exception of a series of samples with a thickness of 8 mm, for which a decrease in strength of more than 11% was noted). Tests conducted on two sets of samples (5 and 8 mm) with smooth ground edges showed a decrease in strength when compared to the samples with arrissed edges, which indicates that the grinding process influences the appearance of Griffith fractures in the ground glass. Tests conducted on a set of samples with a thickness of 8 mm with polished edges showed an improvement in strength characteristics as compared with the samples with lower-quality edge processing.

Tests conducted on a third set of samples with a thickness of 8 mm and smooth ground edges without security film (and with security film with thicknesses of 0.11 and 0.22 mm) showed an increase of 21.7% in the strength of the samples with 0.11 mm film as compared to the samples without security film, while for samples with 0.22 mm security film, the increase in strength was 27.5% when compared to the samples without film. The application of thicker security film to samples with a thickness of 8 mm and polished edges gave the best strength results of all combinations under consideration.

Tests on the influence of the placement of the openings used for mounting glass screens indicated that, in the case of openings placed at a distance of $b = 70$ mm from the longer edge of the screen, a slightly more favorable result was obtained when the openings were placed further from the shorter edge ($a = 40$ mm) than when they were placed closer; however, in both cases ($a = 40$ mm and $a = 22$ mm), the difference in the average breaking force was not big. When the openings were placed at a distance of $a = 40$ mm from the longer edge, reducing the b distance from 70 to 30 mm caused a significant decrease in the average breaking force (exceeding 21.0%).

The tests conducted were used to design glass security screens and a new type of security display case – a closed cassette with a glass screen intended for use in the protection of works of art from acts of vandalism and the influence of unfavorable environmental conditions (Ładecki 2011) (Fig. 6).

Fig. 6. Strength test of display case – closed case with protective glazing

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