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The Structural Strength of Glass: Hidden Damage

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Конструкционная прочность стекла: скрытое повреждение

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Исследуется "скрытое повреждение" стекла в процессе прокатки из-за неравномерного распределения микротрещин в торцевых поверхностях стеклянных конструкционных элементов, которые снижают их прочность и приводят к разрушению. Показано, что при устранении указанных торцевых повреждений существенно повышается конструкционная прочность стекла. С помощью подхода "скрытого повреждения" выполнен статистически обоснованный расчет прочности для наиболее поврежденных образцов с использованием надежного инженерного параметра.

Ключевые слова: стекло, процесс прокатки, скрытое повреждение, инженерный параметр, микротрещины.

Introduction. Glass is commonly used in engineering, when a transparent, durable, and stiff material is needed. Although glass is not usually used for load-bearing applications, in most cases glass still carries a load. In an automobile, the front and rear windows are an integral part of the structure responsible for a significant part of the total stiffness and resisting the considerable forces generated by the air pressure at high-speed driving.

However, the reliable value for the glass strength is an open issue: the tensile strength cannot easily be determined, since glass in direct tensile test will break at the grip. In certain cases, bending test results provide scattered values of the bending strength with a spread of 30 to 50% of the mean strength.

For glass fibers and cast glass the distribution can be adequately described using the Weibull statistic approach leading to a probabilistic strength for the glass used [1, 2]. For the more common float glass this is more complicated. Results of bending experiments by various authors suggest that the processing and specimen size influence the results and suggest systematic data deviation from the Weibull statistic distribution [3–5].

A likely explanation for this is that the usual processing of float glass results in multiple types of defects which provides a multilinear Weibull plot [6, 7].

To investigate this systematically it was decided to look in more depth at the effect of processing on float glass strength. The initial step, which is described in this paper, deals with the effect of cutting and breaking quality on the strength of processed float glass.

Float glass is produced as 6×3.21 m "jumbo" plates. These are cut into the required size and the cut edges are usually grinded and polished. The cutting is usually done by scratching the glass with a glazier's diamond or rolling it with a tungsten carbide roller producing a cut on the upper surface. This is schematically shown in Fig. 1. By bending the plate slightly, as is shown by the arrows, tension is generated at the cut resulting in an unstable crack-cut growing down on the figured straight arrow through the thickness separating the glass parts. Surface damages such as crumbled arrises and cross microcracks are forming on edges of both glass parts under the contact cutter action.

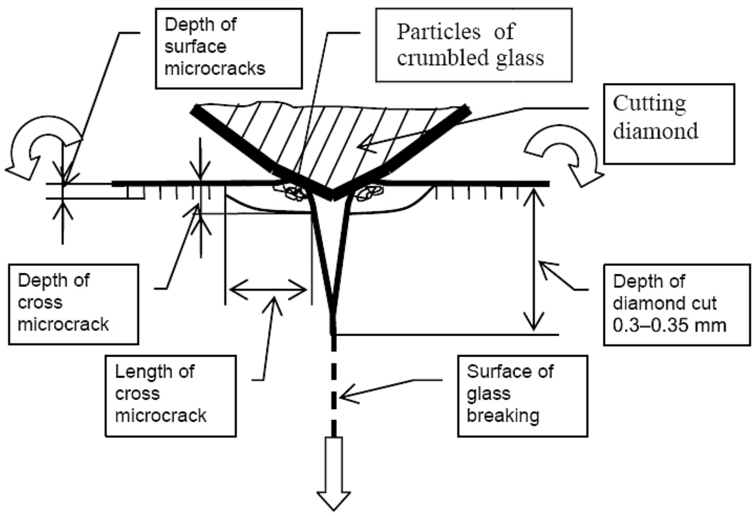


Fig. 1. Diamond cutting and cross microcracks in glass plate elements.

The depth values of these specific cross microcracks are larger than those of the initial surface microcracks which form the cracked surface layer on both sides of float glass. The length of transversal microcracks is typically larger than the width of the cut with the crumbled arrises as seen in Figs. 1 and 2.

Therefore these "invisible" and practically uncontrolled microcracks are root cause for the low strength of cut glass elements. Their sizes may be so large that the deepest of them may remain partially or fully after grinding and polishing of the glass element edges.

For this research 190 pieces of glass with a size of 400×50 mm were cut from a single 6 mm "jumbo" panel using an automated cutting table. The length axis of the specimens corresponds to the width axis of the jumbo plate. These specimens were carefully removed, stacked and shipped.

Specimens were subjected to flat tests with the cut up (i.e., with the cut in the compression zone) and with the cut down (i.e., with the cut in the tension zone).

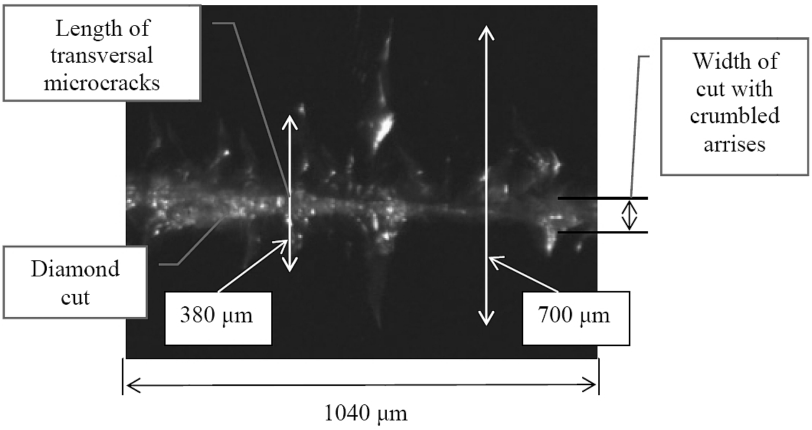


Fig. 2. Transversal microcracks in diamond cut.

In the standing tests, the specimens were tested with the cut left or the cut right relative to the front of the machine. The purpose of the tests was to systematically study the effect of the orientation.

The additional specimens were made more precisely and carefully protected to prevent handling damaging of the edges. These specimens were tested flat with a cut up. Their high quality broken edge arrises were in the tension zone.

Test results were compared with previous data on size effects on glass bending strength with the grinded and polished specimens up to 3.2 m length [8].

Methodology. All four-point bending tests were conducted using a Zwick Z100 universal testing machine under displacement control. Table 1 gives the relevant data. The rig for the standing tests was equipped with friction less antibuckling supports. All glass was wrapped in self adhesive plastic foil for safety. Before test commencement all orientations (top, bottom, left, and right) were indicated on the specimens. After testing specimens were inspected for breakage between the loading span, relative crack origin and number of cracks emanating from the failure point. The tests were conducted in a single week to ensure reasonably constant climatic conditions. During testing no changes were made to the testing machines and the supports. The tests setups are shown in Figs. 3 and 4.

T a b l e 1

Testing Conditions

Orientation	Height (mm)	Width (mm)	Load span (mm)	Support span (mm)	Test speed (mm/min)
Standing test	40	6	175	350	1
Flat test	6	40	175	350	5

Testing of additional specimens was made with flat test orientation under the same testing conditions using a ZD-4 universal hydraulic testing machine under displacement, test speed and loading speed control. Table 2 gives the relevant data. The test setup is shown in Fig. 5.

Table 2

Testing Conditions for Additional Flat Test Specimens with the Cut in Compression

Height (mm)	Width (mm)	Load span (mm)	Support span (mm)	Average test speed (mm/min)	Average loading speed (MPa/s)	Number of specimens
6	40	175	350	4.80	1.590	6
				0.49	0.162	5

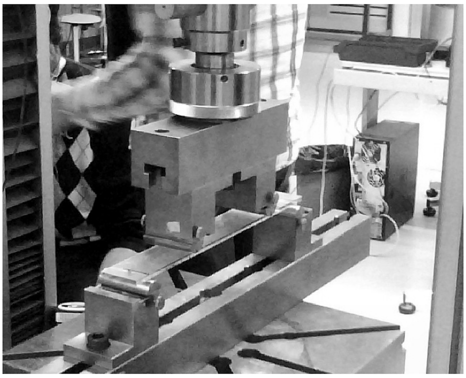


Fig. 3. Test setup for flat tests.

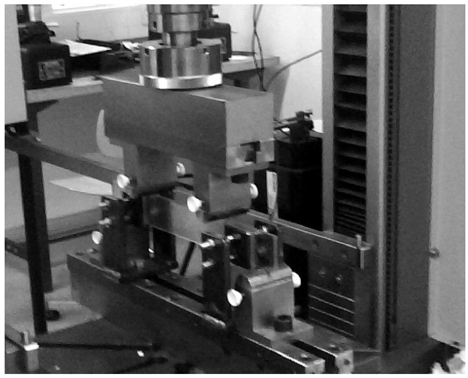


Fig. 4. Test setup for standing tests.

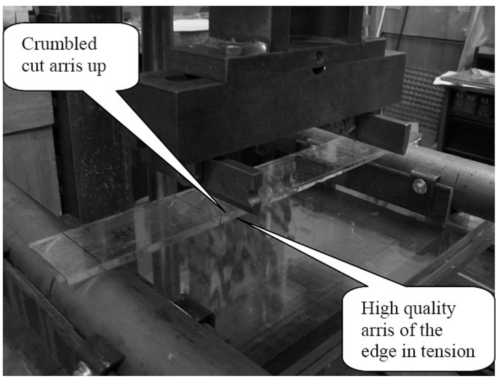


Fig. 5. Test setup for additional specimens in flat tests.

Results. The results of the flat tests are given in Table 3. Figure 6 shows a Weibull plot of the flat results with the cut in the compression zone. Figure 7 shows a Weibull plot of the flat test results with the cut in the tensile zone.

The results from the standing tests are given in Table 4. Figure 8 shows a Weibull plot of the standing results with the cut left. Figure 9 shows a Weibull plot of the standing results with the cut right.

Statistical Analysis. As there is doubt about the suitability of the Weibull distribution, the data has been analyzed using the following distributions:

(i) normal;

(ii) lognormal;

(iii) extreme value;

(iv) exponential;

(v) Rayleigh;

(vi) Weibull.

T a b l e 3

Results of Flat Tests

No.	F cut down (N)	$\sigma_{b,\max}$ cut down (MPa)	Break between loading span (yes/no)	Crack from left or right	Number of cracks	F cut up (N)	$\sigma_{b,\max}$ cut up (MPa)	Break between loading span (yes/no)	Crack from left or right	Number of cracks
1	2	3	4	5	6	7	8	9	10	11
1	357	52.06	yes	left	13	259	37.77	yes	left	3
2	335	48.85	yes	right	6	447	65.19	yes	right	14
3	351	51.19	yes	right	5	413	60.23	yes	left	17
4	382	55.71	yes	left	9	373	54.40	yes	right	15
5	405	59.06	yes	right	11	414	60.38	yes	right	13
6	352	51.33	yes	right	9	365	53.23	yes	right	8
7	364	53.08	yes	right	6	463	67.52	yes	right	12
8	356	51.92	yes	right	5	467	68.10	yes	left	16
9	386	56.29	yes	left	8	470	68.54	yes	right	10
10	347	50.60	yes	right	6	400	58.33	yes	left	9
11	328	47.83	yes	left	7	431	62.85	yes	left	14
12	248	36.17	yes	left	1	360	52.50	yes	left	6
13	340	49.58	yes	right	8	381	55.56	yes	left	10
14	350	51.04	yes	left	10	361	52.65	yes	right	8
15	377	54.98	yes	left	9	398	58.04	yes	right	8
16	368	53.67	yes	right	13	375	54.69	yes	right	14
17	382	55.71	yes	right	9	408	59.50	yes	right	23
18	380	55.42	yes	right	8	432	63.00	yes	left	15
19	375	54.69	yes	left	18	343	50.02	yes	left	5
20	396	57.75	yes	right	7	301	43.90	yes	left	4
21	340	49.58	yes	right	9	442	64.46	yes	left	11
22	361	52.65	yes	left	7	290	42.29	yes	right	4
23	343	50.02	yes	right	9	369	53.81	yes	right	10
24	383	55.85	yes	left	17	467	68.10	yes	right	15
25	366	53.38	yes	right	8	512	74.67	yes	left	19
26	305	44.48	yes	left	10	275	40.10	yes	right	7
27	341	49.73	yes	left	14	485	70.73	yes	middle*	n.a.
28	397	57.90	yes	middle	n.a.	434	63.29	yes	right	16
29	286	41.71	yes	right	11	554	80.79	yes	left	33
30	384	56.00	no*	right	n.a.	683	99.60	yes	right	36
31	303	44.19	yes	left	12	402	58.63	yes	right	8
32	354	51.63	yes	right	10	656	95.67	yes	middle*	n.a.

Continued Table 3

1	2	3	4	5	6	7	8	9	10	11
33	395	57.60	yes	right	3	302	44.04	yes	right	4
34	238	34.71	yes	right	14	364	53.08	yes	middle*	n.a.
35	329	47.98	yes	right	2	470	68.54	yes	right	17
36	378	55.13	yes	right	14	349	50.90	yes	right	8
37	337	49.15	yes	right	15	396	57.75	yes	left	20
38	327	47.69	yes	right	14	532	77.58	yes	left	16
39	335	48.85	yes	left	12	383	55.85	yes	left	9
40	379	55.27	yes	left	15	539	78.60	yes	right	21
41	–	–	–	–	–	559	81.52	yes	left	23
42	–	–	–	–	–	418	60.96	yes	left	9
43	–	–	–	–	–	455	66.35	yes	left	29
44	–	–	–	–	–	257	37.48	yes	right	3
45	–	–	–	–	–	469	68.40	yes	right	17
46	–	–	–	–	–	440	64.17	yes	left	21
47	–	–	–	–	–	544	79.33	yes	left	29
48	–	–	–	–	–	505	73.65	yes	middle*	n.a.
49	–	–	–	–	–	517	75.40	yes	left	16
50	–	–	–	–	–	446	65.04	yes	right	18
Mean		51.6	left	38%			61.4	left	47.8%	
std/mean		10.6%					20.5%			
maximum		59.1					99.6			
minimum		34.7					37.5			

Note. Here and in Table 4: results with * are excluded from calculations and graphs.

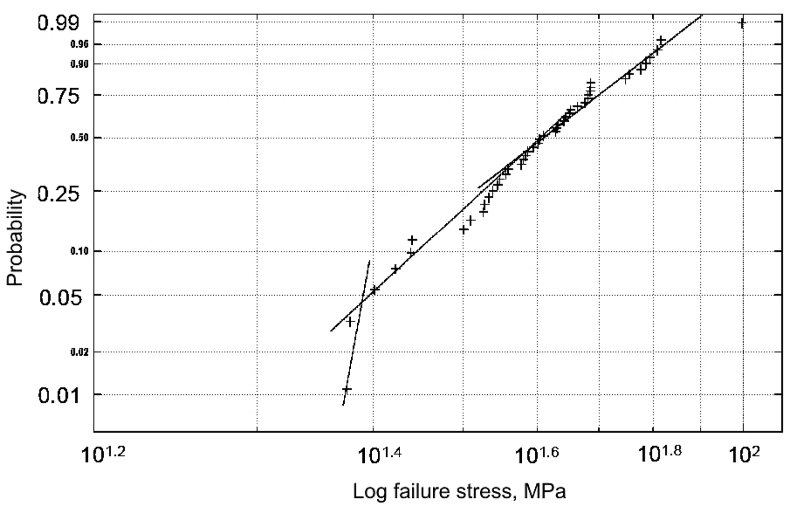


Fig. 6. Weibull plot of flat test results with the cut upwards.

Table 4

Results of Standing Tests

No.	F cut left (N)	$\sigma_{b,\max}$ cut left (MPa)	Break between loading span (yes/no)	Number of cracks	F cut right (N)	$\sigma_{b,\max}$ cut right (MPa)	Break between loading span (yes/no)	Number of cracks
1	2	3	4	5	6	7	8	9
1	2770	48.48	yes	5	3730	65.28	yes	4
2	2800	49.00	yes	5	3620	63.35	yes	9
3	2450	42.88	yes	4	3450	60.38	yes	7
4	2430	42.53	no*	n.a.	3550	62.13	yes	7
5	2860	50.05	yes	7	3010	52.68	yes	5
6	2830	49.53	yes	4	2890	50.58	yes	7
7	3290	57.58	yes	6	2780	48.65	yes	5
8	2970	51.98	yes	5	2900	50.75	yes	6
9	2860	50.05	yes	5	2530	44.28	yes	6
10	2750	48.13	yes	5	3560	62.30	yes	9
11	2260	39.55	yes	5	2740	47.95	no*	n.a.
12	2740	47.95	yes	6	2950	51.63	yes	5
13	1820	31.85	yes	2	2500	43.75	no*	n.a.
14	2510	43.93	yes	4	3020	52.85	yes	6
15	2560	44.80	yes	5	2790	48.83	yes	6
16	2500	43.75	yes	4	3010	52.68	yes	5
17	2970	51.98	yes	5	2730	47.78	yes	5
18	2710	47.43	yes	4	2130	37.28	yes	4
19	2240	39.20	no*	n.a.	3120	54.60	yes	7
20	2590	45.33	no*	n.a.	3350	58.63	no*	n.a.
21	1990	34.83	yes	3	2650	46.38	no*	n.a.
22	3120	54.60	yes	6	3950	69.13	yes	9
23	3190	55.83	yes	6	3110	54.43	yes	6
24	2240	39.20	yes	3	2710	47.43	yes	6
25	2470	43.23	yes	4	3050	53.38	yes	5
26	3080	53.90	yes	7	3340	58.45	yes	7
27	2440	42.70	yes	4	3190	55.83	yes	7
28	2800	49.00	yes	6	2930	51.28	no*	n.a.
29	2320	40.60	yes	5	2760	48.30	no*	n.a.
30	2310	40.43	yes	4	2260	39.55	yes	4
31	3150	55.13	yes	8	3420	59.85	yes	8

Continued Table 4

1	2	3	4	5	6	7	8	9
32	2890	50.58	yes	5	3140	54.95	yes	7
33	2930	51.28	yes	6	3370	58.98	yes	6
34	2600	45.50	yes	4	3250	56.88	yes	7
35	2290	40.08	yes	5	1870	32.73	yes	2
36	2400	42.00	yes	4	3960	69.30	yes	8
37	2660	46.55	yes	5	3400	59.50	yes	7
38	3080	53.90	yes	6	3400	60.20	yes	9
39	3610	63.18	no*	n.a.	3480	60.90	yes	9
40	3460	60.55	yes	6	3200	56.00	yes	8
41	2680	46.90	yes	5	3540	61.95	yes	9
42	2640	46.20	yes	6	3270	57.23	yes	7
43	3500	61.25	yes	9	3180	55.65	yes	8
44	2120	37.10	no*	n.a.	2380	41.65	yes	6
45	3120	54.60	yes	6	3090	54.08	yes	7
46	2970	51.98	yes	6	2810	49.18	yes	6
47	2330	40.78	no*	n.a.	3000	52.50	yes	5
48	2690	47.08	yes	4	3550	62.13	yes	10
49	3120	54.60	yes	6	2910	50.93	yes	7
50	2380	41.65	yes	3	2960	51.80	yes	6
Mean		47.9				54.3		
std/mean		13.5%				14.3%		
maximum		61.3				69.3		
minimum		31.9				32.7		

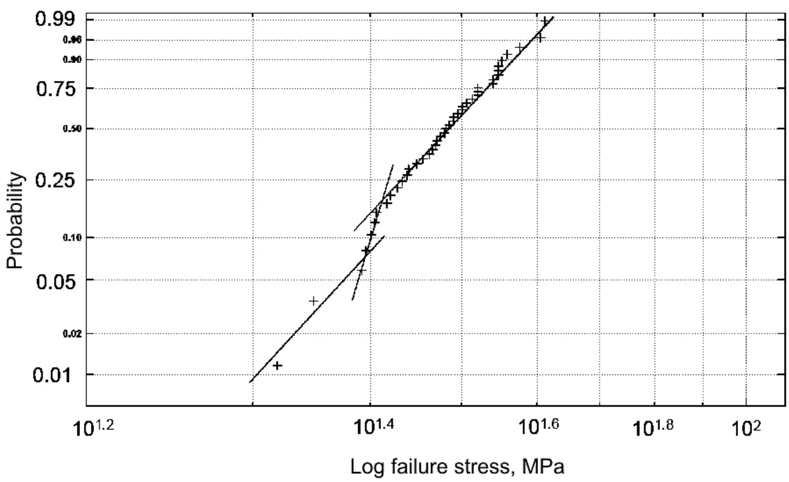


Fig. 7. Weibull plot of flat test results with the cut downwards.

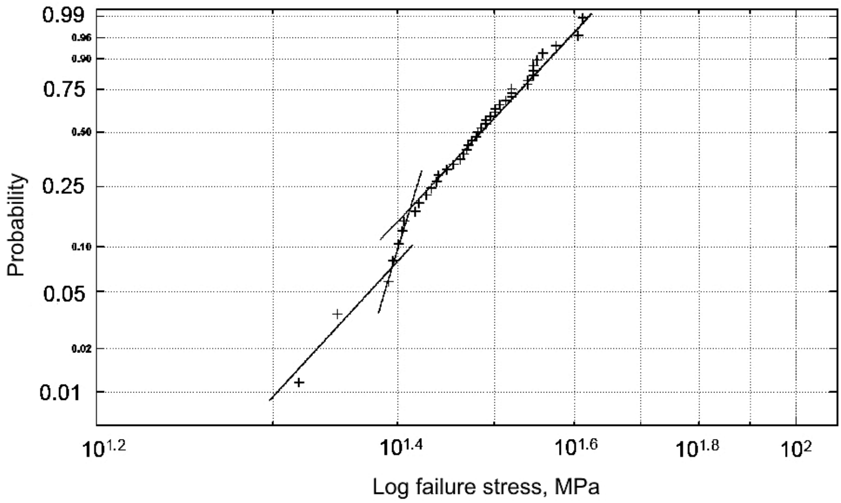


Fig. 8. Weibull plot of standing test results with the cut left.

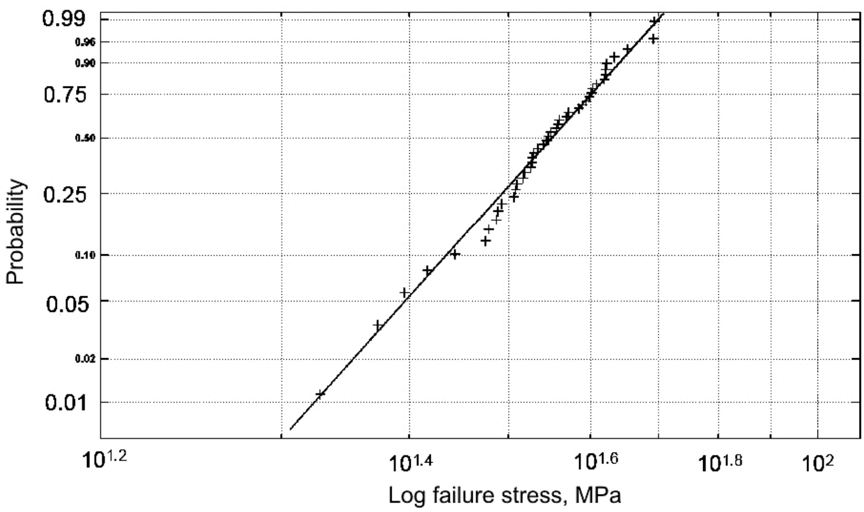


Fig. 9. Weibull plot of standing test results with the cut right.

These are analyzed using normal probability plots for the best fit of the distribution. If the points fall on the straight line the distribution fits. In general, the problem lies at the maximum and minimum values. Only in some cases a reasonable fit occurs. This is given in Table 5 and Figs. 10–12. In practice. there is no single statistical descriptor that gives a universal fit on all valid test results.

Analysis of Partial Data Sets. By splitting the cut up and cut down data sets for flat tests into subsets with fracture from the left or from the right we obtain the Weibull plot shown in Fig. 13. The partial data sets seem to fit the Weibull function better than the mixed data sets. The extremes at top and bottom are again the problem.

Figure 14 shows the cut left data (standing tests), separated to failure from the cut and failure not from the cut. The partial data set for failure not from the cut fits the Weibull function much better (Fig. 14a and curve *1* in Fig. 14b). For the failure

Table 5

Fits to Different Statistical Functions

Distribution	Cut up	Cut down	Cut left	Cut right
Normal	no	no	yes	no
Lognormal	no	no	yes	no
Extreme value	no	yes	no	yes
Exponential	no	no	no	no
Rayleigh	no	no	no	no
Weibull	no	no	yes	yes

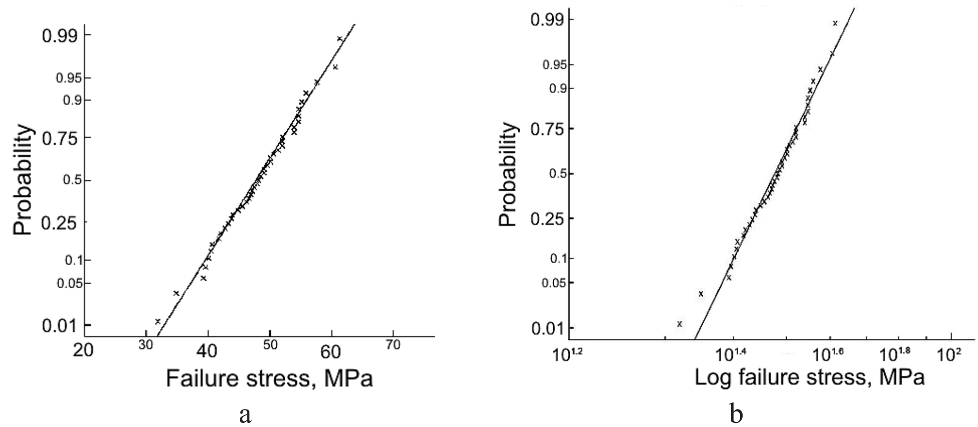


Fig. 10. Normal (a) and lognormal (b) distribution plot for cut left data set (standing).

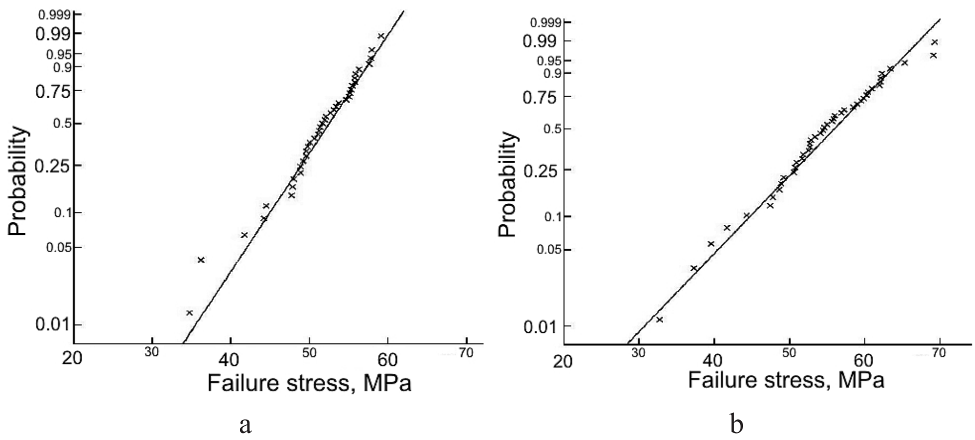


Fig. 11. Extreme value distribution probability plot for cut down – flat tests (a) and cut right data set – standing tests (b).

from the cut (curves *2* and *3* in Fig. 14b) the bimodal Weibull function is better on account of three lowest strength values deviate (curve *3* in Fig. 14b).

Fractography. A microscope was used to look at the failure origins. For the standing cut right series all failures started at the cut. This is shown in Fig. 15. The depth of cut as well as crumbled arris of cut are clearly visible in the butt of the cut glass specimen.

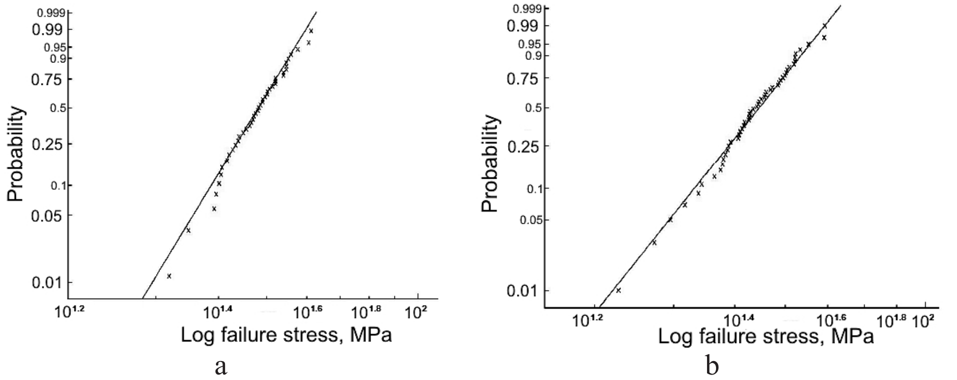


Fig. 12. Weibull distribution probability plot for cut left (a) and cut right (b) data set (standing tests).

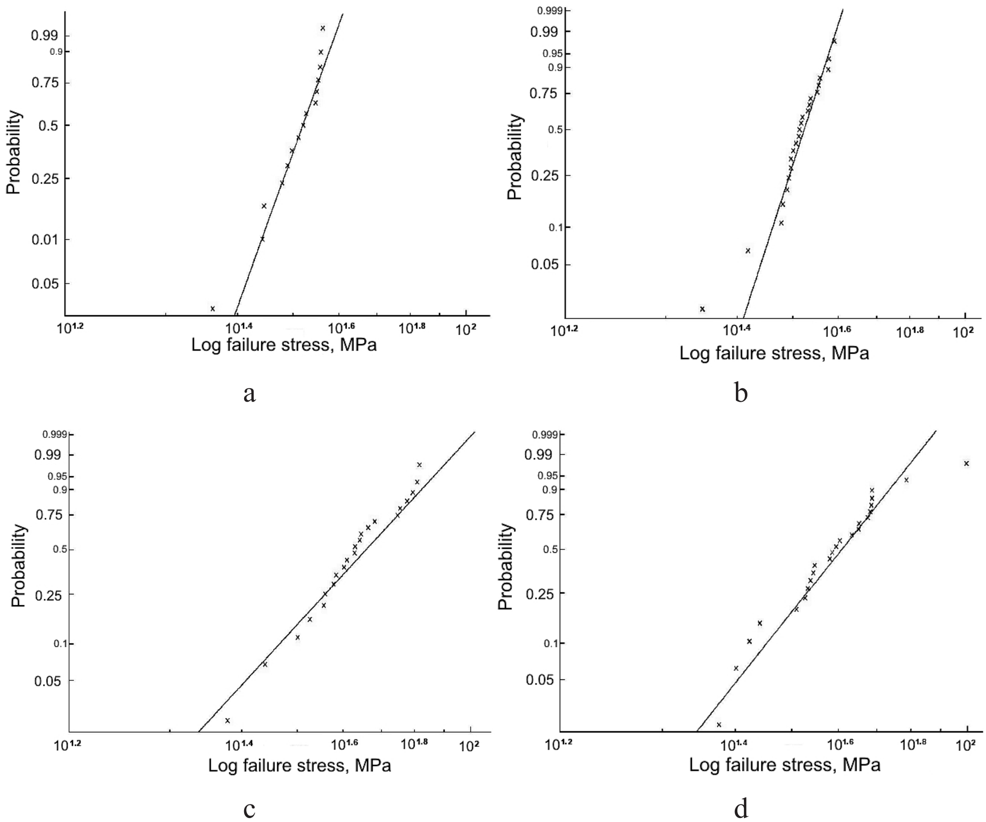
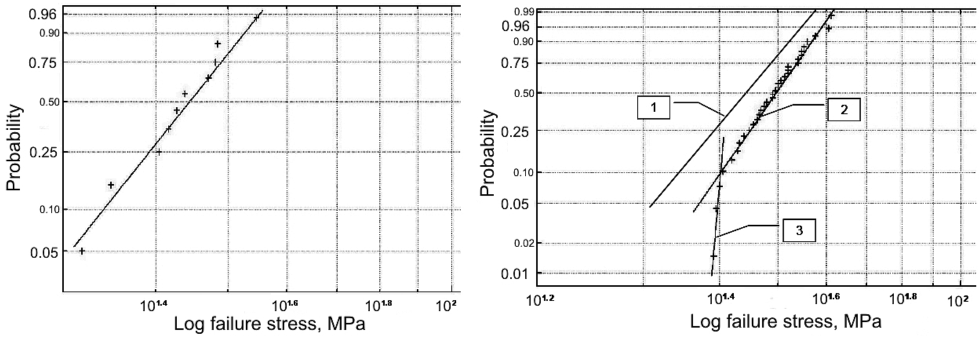


Fig. 13. Weibull plot of data subdivided into: fracture from left (a) or right (b) for the cut down data sets and from left (c) or right (d) for the cut up data sets (flat tests).

Fractographic analysis of the cut left data shows that of 44 valid results 34 specimens failed from the cut and 10 from the other side. Figure 16 shows a failure from the damaged arris on the uncut side of specimen.

Relation between Number of Cracks and Failure Stress. Figure 17 shows a plot between the number of cracks branching from the failure point and the failure stress. There is an approximately linear relation with very large deviations. However, the slopes of flat and standing tests differ by a factor of three.



a b

Fig. 14. Weibull plot of cut left data (standing tests) subdivided into: fracture not from cut (a) and (b, curve *1*), and fracture from cut (b, curves *2* and *3*).

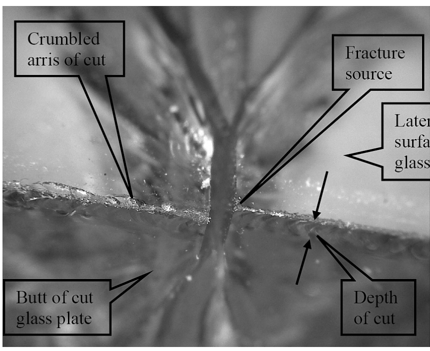


Fig. 15

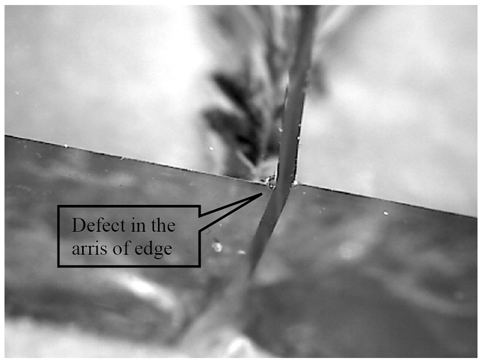


Fig. 16

Fig. 15. Failure point of cut right standing specimen No. 50 (Table 5), ×30.
Fig. 16. Failure from the damaged arris in the uncut side in cut left specimen No. 30 (Table 5).

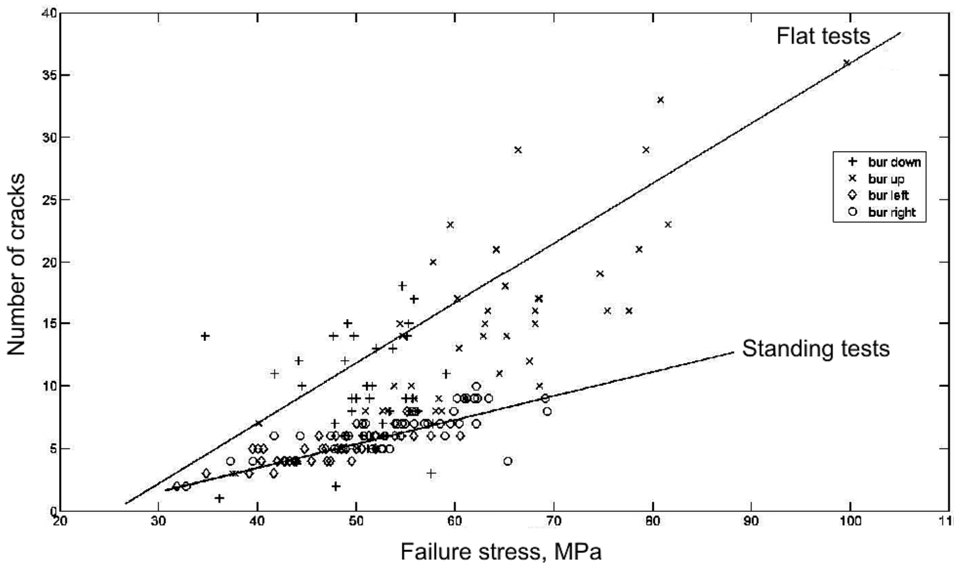


Fig. 17. Relation between the number of cracks and the failure stress.

Strength of Cut Specimens with a High-Quality Broken Arris of the Edge. The results from the flat tests of additional specimens with a high-quality cut glass edge working and safely handled are given in Table 6. The undamaged broken edge arris of these specimens was in the tension zone.

Table 6

Results of the Flat Tests for Specimens with High-Quality Broken Arris

No.	$\sigma_{b\,\max}$, MPa	Test speed, mm/min	Loading speed, MPa/s	Mean value of $\sigma_{b\,\max}$, MPa	std/mean, %	Maximum value of $\sigma_{b\,\max}$, MPa	Minimum value of $\sigma_{b\,\max}$, MPa
1	148	4.900	1.560	146	15	160	114
2	151	4.920	1.600				
3	114	4.660	1.520				
4	157	4.930	1.600				
5	160	4.770	1.600				
6	145	4.950	1.610				
7	137	0.494	0.161	149	11	170	131
8	131	0.488	0.158				
9	162	0.526	0.170				
10	147	0.492	0.160				
11	170	0.497	0.161				

Discussion. A significant amount of results have been presented. There are several possible conclusions that can be drawn from this. The most important is that the cutting process produces unequal sides. There is a significant effect if the cut is the source of failure. The average strength is some 20% less compared with the tests where the cut is on the compression side. The data is however much more homogeneous. The relative standard deviation is half compared to the tests where the cut is on the compression side. Even if both sides would follow a perfect Weibull distribution, the mixed data would not give a good Weibull distribution. As the Weibull distribution of both sets is considerably less than perfect, any resultant combination of course should totally deviate.

The statistical analyses initially suggest that there is no single distribution that fits all data. Of course this would only be valid if the data sets are really the result of a single causative operation and are independent. At best the statistical results can indicate that there is no single valid parameter or that the Weibull parameter is better or worse than any other parameter.

More interesting is the good fit for the standing tests with the cut on the right. There can be a deterministic explanation for this. Glass is an unyielding material and it is very unlikely that the test setup places the specimen perfectly straight. More likely is a small misalignment such as shown, exaggerated, in Fig. 18. This would explain the relatively high number of failures from the upper loading which go outside of the area between the loading span as the load would be transferred mostly onto an edge. In the tensile zone, the cut would be the most highly stressed part, especially the corner edge. Apparently the misalignment forces the specimens to fail from a single geometrical position and thus results in a single Weibull distribution.

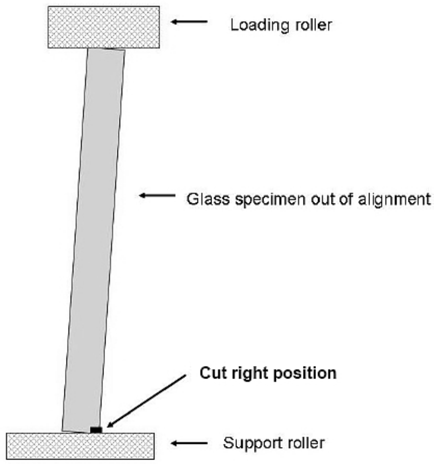


Fig. 18. Proposed alignment problem for the cut right standing tests.

If we compare the Weibull plots of the partial flat specimen data sets, separated to failure from the left and from the right in Fig. 13 an improved Weibull fit is visible, especially for the bur-down tests (Fig. 13a and b). The higher homogeneity of damages under glass cutting is the cause of that.

Presumably by separating the data further to source of fracture we might be able to obtain a series of single Weibull lines. The inherent multilinear Weibull behavior of cut float glass is thus the result of combining incomparable data sets.

If the cut glass is grinded and polished, the edges should become more equal. The reality of any process is of course that it has statistical results. The authors have regularly seen glass that has been grinded and polished, even tempered, on which parts of the cut or original crumbled arris of cut are still visible. In one case glass went into a tempering furnace with the cut surface still visible on about 50% of the edge surface.

Even if just enough of the glass was grinded to remove the bur and the protruding edge areas, the excess forces applied during the grinding could easily cause further surface microcrack growth and microdamage at areas of very poor surface quality. In any case, it would be impossible to see the original orientationon the grinded surface. As the data sets for grinded and polished large-size glass specimens are similar to those of cut glass, it is reasonable to assume that invisible damage from the cutting process influences the failure process of grinded and polished glass as shown in Fig. 19.

The standing test results allow us to evaluate the most probable lower value of glass plate strength as they include damages on all edge surfaces – on the Tin, nitrogen sides and bur as well as damages on both arrises. The Weibull plots of diamond cut specimens standing test results based on the data of Table 5 together with previous experimental data on size effect influence on grinded and polished glass strength (Table 2, Fig. 10 [8]) are given in Fig. 19.

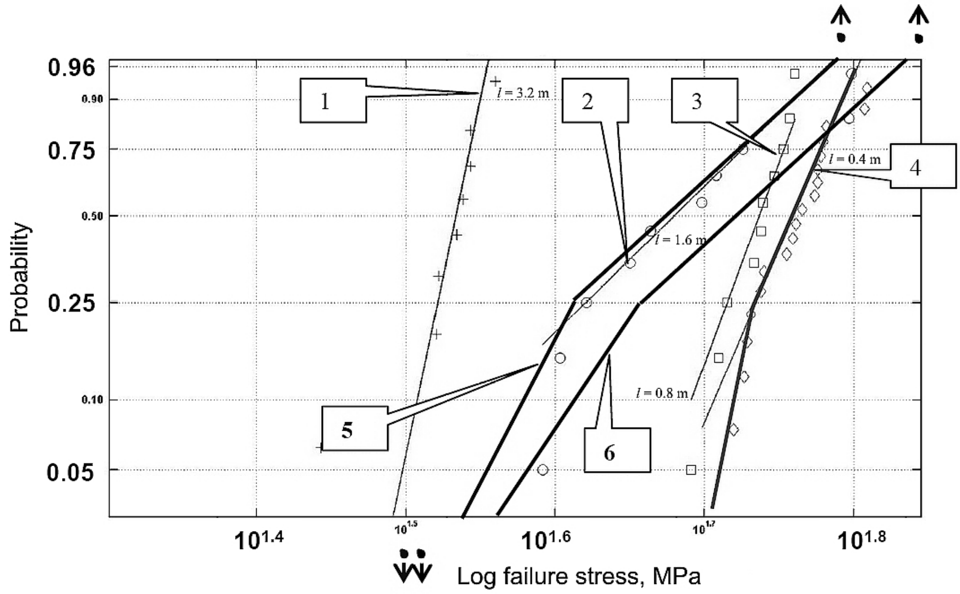


Fig. 19. Weibull plot of standing test results with cut edge left and right in reference to roller cut, grinded, and polished specimens with different load span: (*1*) $l = 0.9$ m; (*2*) $l = 0.45$ m; (*3*) $l = 0.225$ m; (*4*) $l = 0.1125$ m, roller cut, grinded, and polished [1]; (*5*) $l = 0.175$ m, diamond cut, cut edge left; (*6*) $l = 0.175$ m, diamond cut, cut edge right.

Curves *1–4* show the test results for 8 mm float glass grinded and polished specimens series A, B, C and D with a load span $l = 0.9$, 0.45, 0.225, and 0.1125 m [8]. For comparison with these data the curves *5* and *6* for diamond cut 6 mm specimens with cut left and cut right are given. It is obvious that angle of slope of lower part of multilinear curves *4*, *5*, and *6* is closer to angle of slope of single Weibull line *1* for large-size specimens. But the minimal strength value for small grinded and polished specimens (curve *4*) is significantly larger than the minimal value of large specimens (curve *1*) as a result of large difference of their edge “hidden damages.” Quite the contrary, curves *5* and *6* are close to curve *1* for probability of fracture less than 0.05. Thus, low-quality processing and rough handling are the reasons for “hidden damage” effect on engineering strength of float glass.

This approach is corroborated by the new test results on the strength of specimens with a high-quality edge given in Table 6. The minimal strength values for both series of specimens of 6 mm float glass tested at various loading speeds are within the range of 115–130 MPa, which is more than twice higher than that of the grinded and polished specimen series C and D in flat tests (60 and 50 MPa) [8]. Standard deviation for these specimens' strength was comparable with series S and D – within the range of 10–15% of average. Average values 145–150 MPa and the maximal values of strength 160–170 MPa reach the level of fully tempered glass strength. In contrast to tempered glass, fracture of these high-strength specimens was localized around the fracture source. Very small “central” surface defects – microcracks on side face are typical for tested high-quality float glass specimens. Just these initial microcracks in the thin cracked surface layer of high-quality sheet glass are the fracture source in the absence of large edge or side face "hidden damages" of glass elements.

These results show that "hidden damages" are the reason for the low structural strength of glass in usual practice. But these damages may be controlled and eliminated using the proposed approach and experimental data on glass structural strength together with advanced glass processing technology and industrial methods of structural glass strength control.

Conclusions

1. The side of the glass that is rolled or scratched to create the cut is on average by 20% weaker than the other side.

2. The failure stress of the side of the glass that was rolled to create the bur is much more consistent than the results obtained with specimen failure from the other side.

3. The failure stress of the side opposite to the bur can be much higher than strength of specimens with cut edge in tension as well as than strength of ordinary mechanically treated specimens, reaching values of heat-strengthened and even fully tempered glass.

4. If failure is forced from a single part of the cut area, a single mode Weibull distribution is obtained.

5. If the data are sorted out according to failure from left or right and from cut side or uncut side, the Weibull distributions of the partial data sets are better than those of the combined data sets.

6. The multilinear Weibull pattern of the mixed data of the cut glass is similar to that of grinded and polished glass.

7. It is suggested that invisible damage from the cutting process remains after grinding and polishing and is the underflat cause of the multilinear Weibull behavior.

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Резюме

Досліджується "приховане пошкодження" скла у процесі прокатки через нерівномірний розподіл мікротріщин у торцевих поверхнях скляних конструкційних елементів, які, знижуючи їх міцність, зумовляють руйнування. Показано, що усунення вказаних торцевих пошкоджень суттєво підвищує конструкційну міцність скла. За допомогою підходу "прихованого пошкодження" виконано статистично обгрунтований розрахунок міцності для найбільш пошкоджених зразків із використанням надійного інженерного параметра.

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