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The strength of glass, hidden damage

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The strength of float glass is a necessary engineering parameter. Determining this strength is a complex problem. Earlier results have shown that statistically bending test results are not a homogeneous group. To explain this, a theory of "hidden damage" is proposed. The essence of this theory is that the different sides of float glass are unequal, not only because of the differences between the Tin and nitrogen sides, but because of the difference between the side scored under the sheet glass cutting and the side which has the crack propagation from the scored side in breaking. Extensive tests on rolled glass suggest that the rolling process damages the glass in a special way, causing "invisible" damage – statistically not a homogeneous distribution of micro-cracks on the edge surface of glass element. These micro-cracks are different on the scored and broken sides of glass. They are the fracture source under the loading and influence negatively on glass element strength and statistics of strength data.This "invisible" damage explains most if not all of the non-homogenous distribution of the test results. It is shown that removal of this damage on the edges of glass elements increases the engineering strength of float glass significantly.

Keywords: Glass strength, statistical distribution

1. Introduction

Glass is commonly used in engineering. It is used when a transparent, durable, 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.

For all this there is no reliable value for the strength of glass. The tensile strength cannot easily be determined as in direct tensile test the glass will break in or at the grip. Bending test results give a scattered value for the bending strength, with a spread of some 30 to 50% of the mean strength in certain cases.

For glass fibres and cast glass the distribution can usually be described adequately using Weibull statistics 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 influences the result and suggests that the data systematically deviates from the Weibull statistic distribution [3,4,5]. A likely explanation for this is that the usual processing of float glass results in multiple types of defects which results in a multi linear 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 ground and polished. The cutting is usually done by scratching the glass with a glazier's diamond of rolling it with a tungsten carbide roller producing a bur on the upper surface. This is schematically shown in figure 1. By bending the plate slightly, as is shown by the arrows, tension is generated at the bur 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 arris and cross micro-cracks are forming on edges of both parts under the contact cutter action. The depth of this specific edge transversal micro-cracks is larger than the depth of the initial surface micro-cracks which form the cracked surface layer on both sides of float glass. So these "invisible" and practically uncontrolled micro-cracks are the 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.

2. Methodology

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 with the width axis of the jumbo plate. These specimens were carefully removed, stacked and shipped.

These specimens were tested lying with the bur up, thus with the bur in the compression zone and with the bur down, and thus with the bur in the tension zone. In the standing tests the specimens were tested with the bur left of the bur right relative to the front of the machine. The purpose of the tests was to systematically look at the effect of the orientation.

Typical edges with bur ad without bur are shown in figures 1 and 2.

All four point bending tests were conducted on a Zwick Z100 universal testing machine under displacement control. Table 1 gives the relevant data. The rig for the standing tests was equipped with frictionless anti buckling supports. All glass was wrapped in self adhesive plastic foil for safety. Before test commencement all orientations; top, bottom, left, right; were noted down on the specimens. After the test all 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 the testing no changes were made to the testing machines and the supports. The tests setups are shown in figure 3.

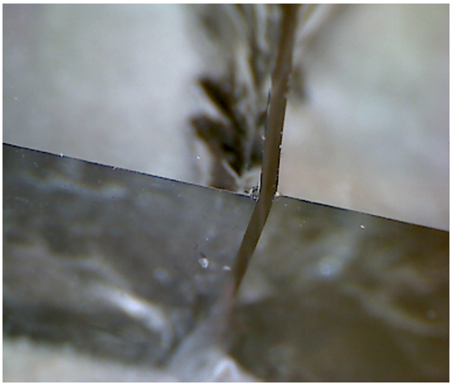

Figure 1: Bur and crack from bur.

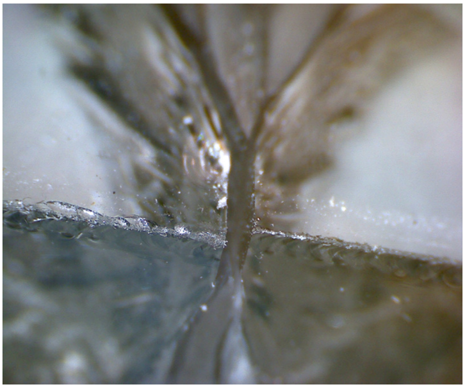

Figure 2: Failure from non-bur edge.

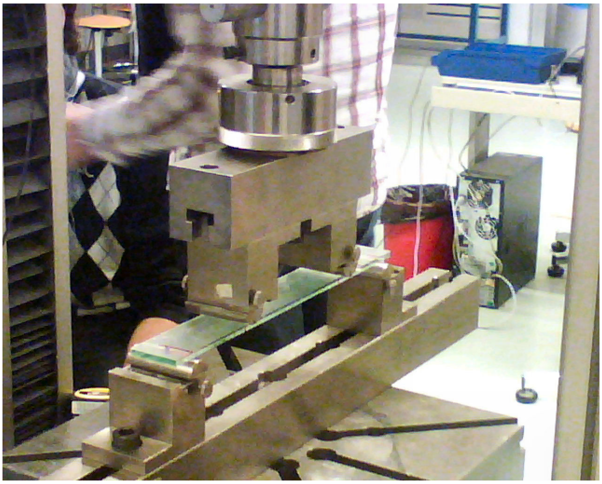

Figure 3:Test setup for lying tests.

Table 1: testing conditions.

Orientation	Height (mm)	Width (mm)	Load span (mm)	Support Span (mm)	Test speed
Standing	40	6	175	350	1 mm/minute
Lying	6	40	175	350	5 mm/minute

3. Results

The results from the lying tests are given in table 2. Figure 4 shows a Weibull plot of the lying results with the bur in the compression zone. Figure 5 shows a Weibull plot of the lying results with the bur in the tensile zone.

The results from the standing tests are given in table 3. Figure 6 shows a Weibull plot of the standing results with the bur left. Figure 7 shows a Weibull plot of the standing results with the bur right.

Table 2: Results from lying tests, results with * excluded from calculations and graphs

Number	$\sigma_{b,max}$ bur down (MPa)	Break between loading span yes/no	Crack from left, right or middle	$\sigma_{b,max}$ bur up (MPa)	Break between loading span yes/no	Crack from left, right or middle	Number	$\sigma_{b,max}$ bur down (MPa)	Break between loading span yes/no	Crack from left, r right or middle	$\sigma_{b,max}$ bur up (MPa)	Break between loading span yes/no	Crack from left, right or middle
1	52.06	y	L	37.77	y	L	26	44.48	y	L	40.10	y	R
2	48.85	y	R	65.19	y	R	27	49.73	y	L	70.73	y	M*
3	51.19	y	R	60.23	y	L	28	57.90	y	M	63.29	y	R
4	55.71	y	L	54.40	y	R	29	41.71	y	R	80.79	y	L
5	59.06	y	R	60.38	y	R	30	56.00	n*	R	99.60	y	R
6	51.33	y	R	53.23	y	R	31	44.19	y	L	58.63	y	R
7	53.08	y	R	67.52	y	R	32	51.63	y	R	95.67	y	M*
8	51.92	y	R	68.10	y	L	33	57.60	y	R	44.04	y	R
9	56.29	y	L	68.54	y	R	34	34.71	y	R	53.08	y	M*
10	50.60	y	R	58.33	y	L	35	47.98	y	R	68.54	y	R
11	47.83	y	L	62.85	y	L	36	55.13	y	R	50.90	y	R
12	36.17	y	L	52.50	y	L	37	49.15	y	R	57.75	y	L
13	49.58	y	R	55.56	y	L	38	47.69	y	R	77.58	y	L
14	51.04	y	L	52.65	y	R	39	48.85	y	L	55.85	y	L
15	54.98	y	L	58.04	y	R	40	55.27	y	L	78.60	y	R
16	53.67	y	R	54.69	y	R	41				81.52	y	L
17	55.71	y	R	59.50	y	R	42				60.96	y	L
18	55.42	y	R	63.00	y	L	43				66.35	y	L
19	54.69	y	L	50.02	y	L	44				37.48	y	R
20	57.75	y	R	43.90	y	L	45				68.40	y	R
21	49.58	y	R	64.46	y	L	46				64.17	y	L
22	52.65	y	L	42.29	y	R	47				79.33	y	L
23	50.02	y	R	53.81	y	R	48				73.65	y	M*
24	55.85	y	L	68.10	y	R	49				75.40	y	L
25	53.38	y	R	74.67	y	L	50				65.04	y	R

mean	51.6	%left	38%	61.4	%left	47.8%
std/mean	10.6%			20.5%		
max.	59.1			99.6		
min.	34.7			37.5		

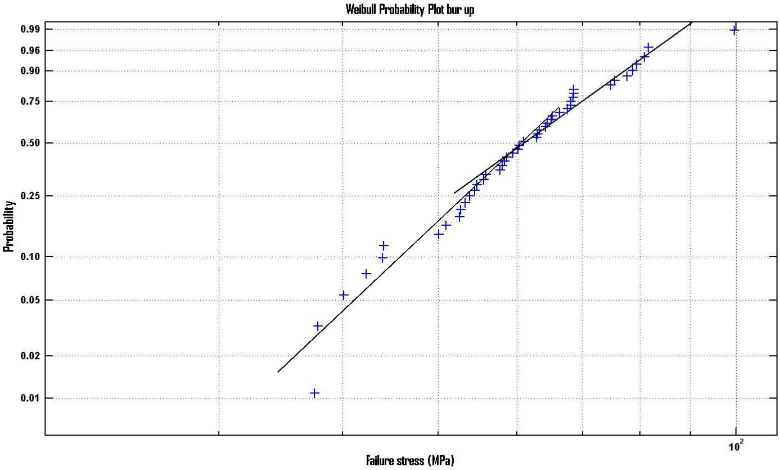

Figure 4: Weibull plot of lying test result with the bur upwards.

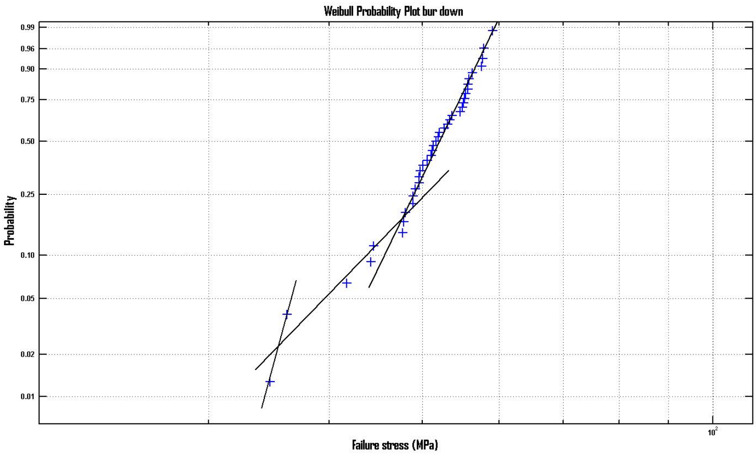

Figure 5: Weibull plot of lying test result with the bur downwards.

Table 3: Results from standing experiments, results with * excluded from calculations and graphs

Number	$\sigma_{b,max}$ bur left (MPa)	Break between loading span yes/no	$\sigma_{b,max}$ bur right (MPa)	Break between loading span yes/no	Number	$\sigma_{b,max}$ bur left (MPa)	Break between loading span yes/no	$\sigma_{b,max}$ bur right (MPa)	Break between loading span yes/no
1	48.48	y	65.28	y	26	53.90	y	58.45	y
2	49.00	y	63.35	y	27	42.70	y	55.83	y
3	42.88	y	60.38	y	28	49.00	y	51.28	n*
4	42.53	n*	62.13	y	29	40.60	y	48.30	n*
5	50.05	y	52.68	y	30	40.43	y	39.55	y
6	49.53	y	50.58	y	31	55.13	y	59.85	y
7	57.58	y	48.65	y	32	50.58	y	54.95	y
8	51.98	y	50.75	y	33	51.28	y	58.98	y
9	50.05	y	44.28	y	34	45.50	y	56.88	y
10	48.13	y	62.30	y	35	40.08	y	32.73	y
11	39.55	y	47.95	n*	36	42.00	y	69.30	y
12	47.95	y	51.63	y	37	46.55	y	59.50	y
13	31.85	y	43.75	n*	38	53.90	y	60.20	y
14	43.93	y	52.85	y	39	63.18	n*	60.90	y
15	44.80	y	48.83	y	40	60.55	y	56.00	y
16	43.75	y	52.68	y	41	46.90	y	61.95	y
17	51.98	y	47.78	y	42	46.20	y	57.23	y
18	47.43	y	37.28	y	43	61.25	y	55.65	y
19	39.20	n*	54.60	y	44	37.10	n*	41.65	y
20	45.33	n*	58.63	n*	45	54.60	y	54.08	y
21	34.83	y	46.38	n*	46	51.98	y	49.18	y
22	54.60	y	69.13	y	47	40.78	n*	52.50	y
23	55.83	y	54.43	y	48	47.08	y	62.13	y
24	39.20	y	47.43	y	49	54.60	y	50.93	y
25	43.23	y	53.38	y	50	41.65	y	51.80	y

mean	47.9		54.3
std/mean	13.5%		14.3%
max.	61.3		69.3
min.	31.9		32.7

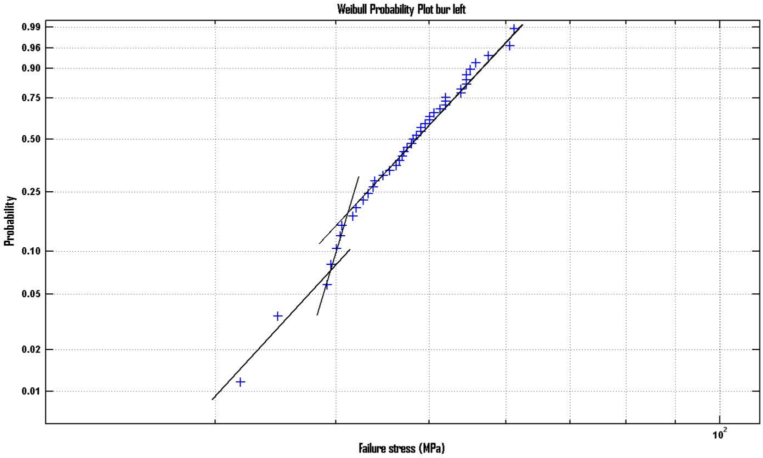

Figure 6: Weibull plot of standing test result with the bur left.

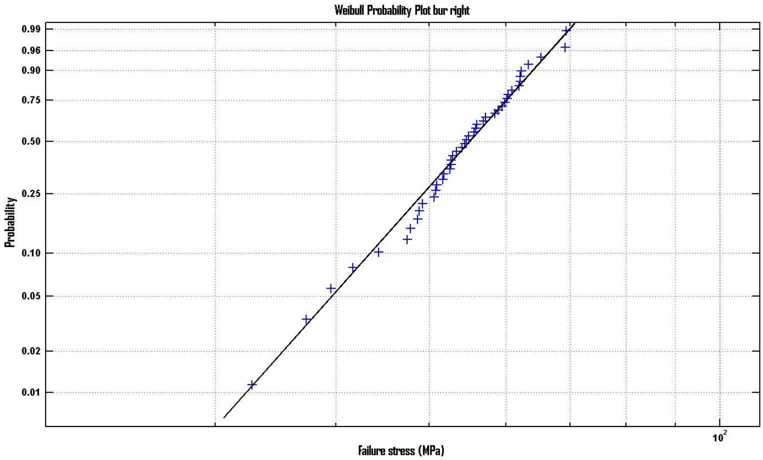

Figure 7: Weibull plot of standing test result with the bur right.

4. Looking at partial data sets

By splitting the bur up and bur down data sets into sub-sets with fracture from the left or from the right we can make the Weibull plots shown in figure 8. 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 9 shows the bur left data separated to failure from the bur and failure not from the bur. The partial data sets fit the Weibull function much better. For the failure from the bur only the three lowest strength values deviate.

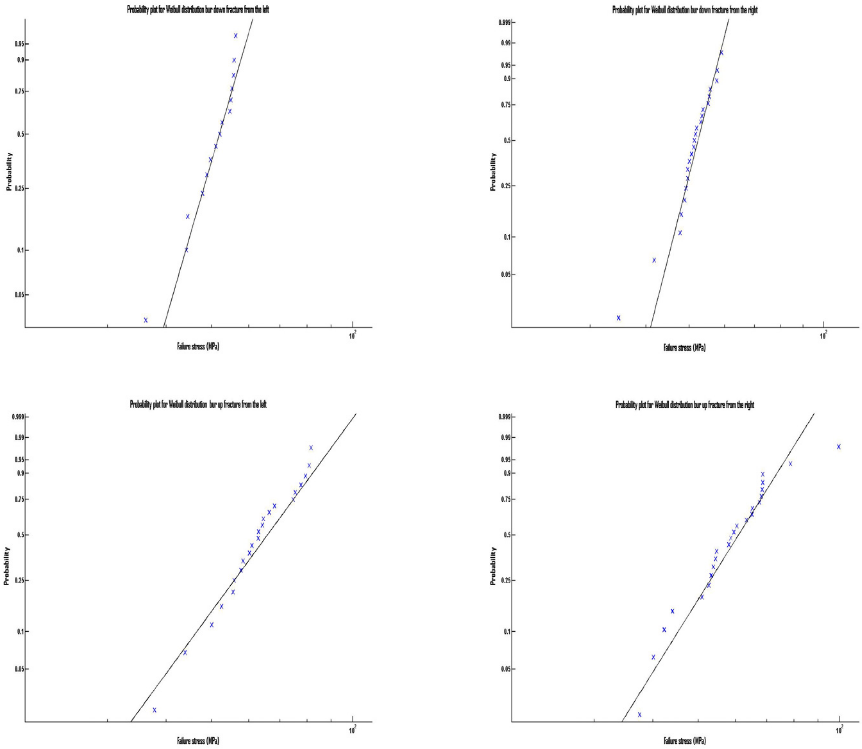

Figure 8: Weibull plot of data divided to fracture from left or right.

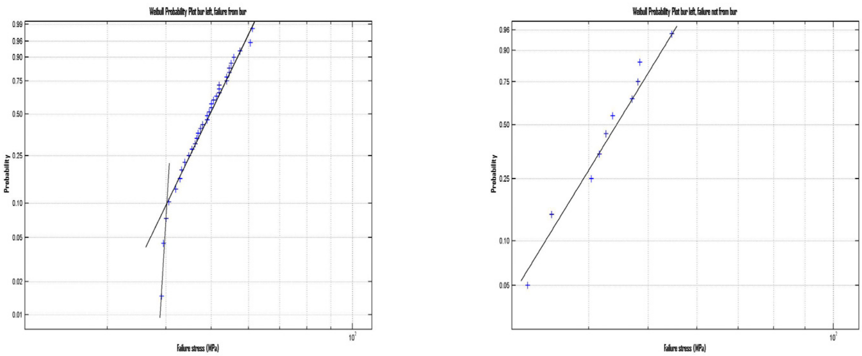

Figure 9: Weibull plot of bur left data, divided to fracture from bur and not from bur.

5. 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 bur is the source of failure.

The average strength is some 20% less compared with the tests where the bur is on the compression side. The data is however much more homogeneous. The relative standard deviation is half compared to the tests where the bur is on the compression side. Even if both sides would follow a perfect Weibull distribution, the mixed data would of course 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 say 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 bur 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. This would explain the relatively high number of failures from the upper loading rolls 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 bur 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.

If we compare the Weibull plots of the partial lying specimen data sets, separated to failure from the left and from the right in figure 8 and compare those with the full lying data sets in the upper pictures in figures 4 and 5, a significantly improved Weibull fit is visible, especially for the bur-down tests.

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

If the cut glass is ground 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 ground and polished, even tempered, on which parts of the bur or original cut surface are still visible. In one case glass went into a tempering furnace with on about 50% of the edge surface the cut surface still visible. The workers who moved the glass from the grinding line to the tempering line did not even notice.

Even if just enough of the glass was ground of to remove the bur and the protruding edge areas, the excess forces applied during the grinding could easily cause further surface micro-crack growth and micro-damage at areas of very poor surface quality. In any case on the ground surface it would be impossible to see the original orientation. As the data sets for ground and polished large size glass are similar to that of cut glass, it is reasonable to assume that invisible damage from the cutting process influences the failure process of ground and polished glass.

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

6. Conclusions

From the results it is concluded that:

- the side of the glass that is rolled or scratched to create the bur is on average some 20% weaker than the other side
- the failure stress of the side of the glass that was rolled to create the bur is much more consistent than the results that failed from the other side
- the failure stress of the side opposite to the bur can be much higher than the strength of specimens with cut edge in tension as well as the strength of ordinary mechanical worked specimens, reaching values for heat strengthened and even fully tempered glass.
- if failure is forced from a single part of the bur area a single mode Weibull distribution results
- if the data is sorted out according to failure from left or right and from bur side or non-bur side the Weibull distributions of the partial data sets are significantly better than for the combined data sets.
- the multi linear Weibull character of the mixed data of the cut glass is similar to that of ground and polished glass.
- it is suggested that invisible damage from the cutting process remains after grinding and polishing and is the underlying cause of the multi linear Weibull behaviour.

7. Conclusions

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