The strength of glass, a nontransparent value

F.A.Veer

Faculty of Architecture, Delft University of Technology, Delft, the Netherlands

f.a.veer@tudelft.nl

The tendency in modern architecture to use glass structurally means that we need to know the engineering properties of glass accurately. The most important of these is the failure strength of glass in bending. Although much work on this has been done and published there are still many questions. These deal mainly with the correct statistical description of the strength of glass, specifically the question whether the Weibull distribution is a satisfactory descriptor. Secondly there is the procedure for determining the design stress of glass.

Experiments have been conducted using large series of specimens treated in several ways. The results show the treatments influence the statistical distribution. Water can result in linear Weibull distributions while other types of glass almost always show bilinear Weibull distributions. A model is proposed which explains the differences between the test series.

Key words: Strength, glass, Weibull distribution

1 Introduction

The strength of glass is used to dimension a structure. This is determined by conducting tensile, bending and sometimes compression tests. The stress at which the material fails is the failure stress while in metals we can also distinguish the stress at which plastic deformation starts, the yield stress. In most engineering materials the failure stress for a large enough test series shows an average and a standard deviation. In homogeneous materials such as Al 7075-T6 this leads to an average and a small standard deviation. In a heterogeneous material such as paper, even with all specimens tested in the fibre direction, there is usually a well enough defined average with a large standard deviation as shown by Veer et al. (2002).

Mechanical testing on soda lime glass gives results which cannot be described using a normal distribution. The strength of glass is determined by the processing. In Aluminium alloys this is also true and the T-xyz suffix stands for the heat treatment and the strength is related to this T-suffix. For glass this is different as processing does not result in significant physical changes in the nonexistent microstructure.

As the strength of glass is important for engineering with glass it has been a topic of research by the author for many years. This paper puts together the results of a series of papers published previously.

1.1 *The structure of glass*

Glass is an amorphous material which is usually taken to mean that there is no structure in glass. This is a wrong assumption. At the nano-level it is possible to identify several primitive shapes in glass. These shapes are rings containing between three and seven Silicium atoms with bridging oxygen atoms in between. These rings are joined into a three dimensional structure by primary chemical (covalent) bonds. Some of these rings are broken up by the OH- groups and Na+ ions of the soda additive. This decreases the melting point by breaking up the 3-D network. Thus although there are some discernible structural elements, there is no systematic repetition of this structure and thus no crystallinity by the standard definition. Glasses outside the soda lime family can have different nano-structures as described by Rouxel (2006). The lack of a crystal lattice prevents dislocations and thus removes any possibility of plasticity. Anyway the covalent bonding between most of the atoms cannot reform easily if broken. Any local stresses around a defect that exceed the chemical bond strength will thus cause bond failure and increase the local stresses. The material can thus only deform elastically or fracture.

1.2 *The processing of glass*

Float glass is made by pouring molten glass onto a bed of liquid tin (Sn) in a nitrogen (N_2) atmosphere. The liquid glass forms a continuous ribbon moving from the hot glass oven to the colder annealing lear, solidifying in the process. Glass thickness is controlled by the rate at which the molten glass is poured onto the tin. The liquid glass is pushed using paddles into a ribbon about 3.5 m wide. In this phase sometimes coatings can be applied to the hot glass on the nitrogen side. After leaving the tin bad the glass ribbon is cooled slowly (annealed) to avoid freezing in residual stresses. The ribbon is cut down to a length of 6 m and later cut to a standard width of 3.21 meter. These standard Jumbo plates are distributed and processed as the needs of the consumer dictate. Quality control is such that there are usually no significant impurities or inclusions in the glass. The controlled cooling leads to a homogeneous plate without internal defects. An often ignored problem is improper annealing. Glass regularly glass cracks spontaneously on the cutting table because of residual stresses. In practice this probably affects less than 0.1% of glass production in western European plants. There are reports that eastern European factories working in winter have much higher levels of annealing problems because of the severity of their winters and poor thermal isolation of factories.

1.3 *Cutting and grinding of glass*

In almost all cases the float glass panels are cut. This is done by scratching a line on the glass using a scoring wheel of high hardness. The glass is bent or heated locally to put the scratch into tension which leads to unstable crack growth from the scratch through the thickness of the plate. Simple as this sounds, it is quite complicated, especially for thicker glass where the crack growth has a more three-dimensional character. Important in all cutting is using the right cutting wheel (hardness and cutting angle), the right lubricant and the right pressure. Too much pressure can cause damage on the back side of the glass. Some aspects of this are explained by Whittle et al. (2002) and Hand et al. (2006). It is important to realise that cut glass by definition is not flat and that the two edges have different geometries.

To give a more even surface and thus better strength the edges of the glass are usually ground. This uses a rotary action to remove material. On a micro level this involves locally cracking the glass into micro fragments which are washed away. The rough surface of the cut glass is transformed into a smooth surface with no visible defects and an assumed higher strength. Grinding can be done to give a flat edge but usually the right angles are ground down to 45 degrees in the belief that this improves the strength. On a given industrial grinder there are several ways to finish the glass. Corti et. al have shown that this affects the strength of the glass. More important than the settings of the machine is the degree of maintenance of the machines. Both for cutting and grinding old and worn down cutting heads or grinding rolls can produce damage which can significantly affect the strength, even if the naked eye cannot be see the differences.

2 Experimental procedure

For all experiments on flat glass, specimens were cut from standard float glass plates. A range of thicknesses has been investigated. The specimens that were manually cut were processed by an experienced glazier using cutting and breaking tools appropriate to the thickness. The machine cut glass was cut using standard industrial automated cutting tables using settings suitable for the glass thickness. Some of the manually cut specimens were finished by sanding or polishing the cut edges. Some of the industrially cut glass had its edges processed using industrial automated grinding equipment.

Some specimens were cut using a water cooled rotary diamond wheel grinder. This produces small specimens with clearly defined and smooth surfaces and square edges in a single processing step.

To find out the strength of noncut glass tests were conducted on Schott AR-glass rods. These have a chemical composition almost identical to soda lime float glass but are produced by an extrusion like process. This results in round bars with a continuous surface.
Zwick Z10 or Z100 universal testing machines were used to conduct bending tests using displacement control. Tests on small specimens used 3 point bending and tests on large specimens used 4 point bending.

Table 1: Overview of test results

Table number	Type of glass	Type of test	Size of specimen	Total number of tests
2	Round bar	3 point bending	400 mm long, 25 mm diameter	10
3	Flat glass, manually cut	3 point bending, tested flat	400×40 mm, 2, 3, 6 mm thick 400×80 mm, 8 mm thick	40
4	Flat glass, manually cut, machine cut, manually cut and sanded and ground out of plate	3 point bending, tested flat	400×40×3 mm	48
5	Flat glass, machine cut, machine cut and ground	3 point bending, tested flat	400×40×6 mm	120
6	Flat glass, Machine cut and ground	4 point bending, Tested flat and standing	600×50×10 mm 1000×125×10 mm 1000×250×10 mm	96
7	Flat glass, Machine cut and ground using three different grinding lines	4 point bending, Tested standing	1000×125×10 mm	32
8	Flat glass and optiwhite glass, ground out from plate	3 point bending, tested flat	200×20×8 mm	139

3 Experimental Results

The tests summarized have been done over a period 7 years. Of each series the average and standard deviation as a percentage of the average are given to compare the spread in different series. Weibull diagrams are shown where they are necessary. This is not done for all tests because of limitations of space.
The use of an average and standard deviation does not imply that a normal distribution is valid. The use is solely for providing a standardised method of comparison. Table 1 contains an overview of the test sets.

3.1 ***Results for noncut glass***

The Schott Ar glass rods were tested in four point bending in the as received condition. The results are given in table 2. Most of these results were published by Veer et al. (2002-2). Failure took place in the centre of the specimens.

Table 2: Bending tests results on AR glass rods of length 400 mm and diameter 25 mm

Glass condition	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
As received	102	6.2	10

3.2 ***Results for manually cut glass***

From standard glass plates of varying thicknesses test specimens were cut by hand and tested in three point bending. The results are given in table 3. These results were published by Veer et al. (2003).

Table 3: Bending strength of manually cut glass, specimens 400 long and 40 mm wide, except for 8 mm thick specimens which were 80 mm wide

Glass thickness (mm)	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
2	50.2	41.0	8
3	74.6	16.8	12
6	62.1	37.2	10
8	47.7	20.2	10

3.3 *Results for three mm thick glass with different edge finishes*

From standard glass plates of 3 mm thick test specimens were cut by hand, by rotary grinding or cut by machine. Some of the manually cut specimens were sanded down to a rounded shape. All specimens were tested in three point bending. The results are summarised in table 4 and shown in figure 1. These results were published by Veer et al. (2003).

Table 4: Bending strength of 3 mm thick glass specimens of length 400 and width 40 mm.

Glass thickness (mm)	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
Manually cut	74.6	16.8	12
Manually cut and sanded to rounded shape	60.3	11.9	12
Ground out of plate	100.2	29.3	12
Machine cut	83.3	39.3	12

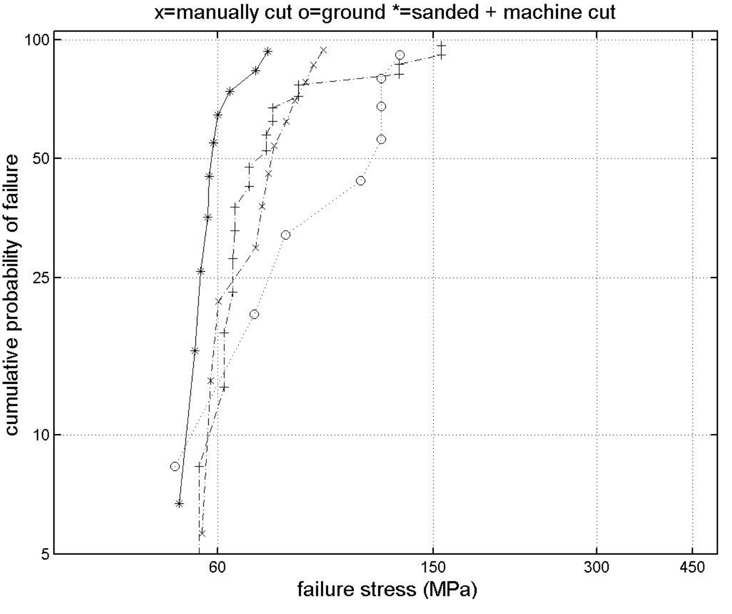


Figure 1: Weibull plot of data in table 4.

3.4 *Results for six mm thick industrially processed glass*

From a single glass plate of 6 mm thickness, test specimens were cut by machine. Some of these were industrially ground on the edges. All specimens were tested in three point bending. The initial results for the cut specimens suggested a division into two groups. The remaining specimens were divided into two groups, which were tested with the cutting bur placed upwards, in the compressive zone, and with the cutting bur placed downwards, in the tensile zone. The result are summarised in table 5 and shown in figure 2. These results were published by Veer et al. (2003)

Table 5: Bending strength of machine cut glass, specimens 400 long and 40 mm wide, 6 mm thick

Test configuration	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
Mixed	65.6	21.7	30
Bur up	100.3	32.8	30
Bur down	49.4	12.6	30
Cut and ground	82.5	8.5	30

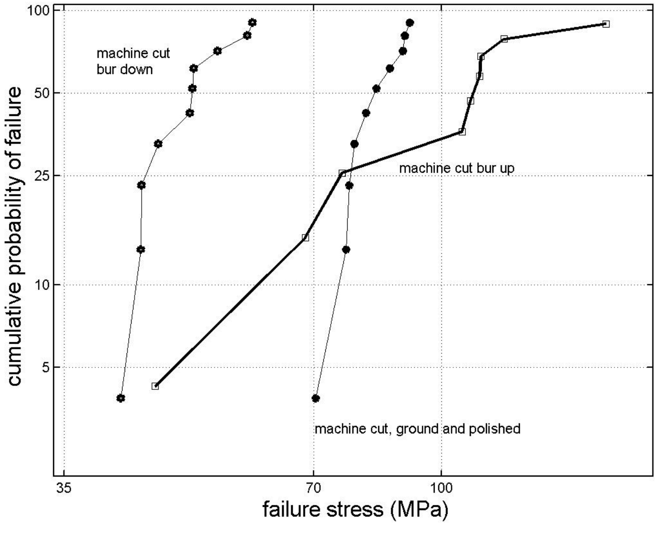


Figure 2: Weibull plot of data in table 5

3.5 ***Results for industrially cut and ground glass***

Large specimens were industrially cut from a single 10 mm glass plate. These were cut into specimens of three different sizes. All specimens were tested in four point bending. Half of the specimens were tested flat and half were tested in a standing position. Following this work the theory was proposed that some of the scatter could be caused by different grinding lines being used. The data is summarised in table 6 and part of it shown in figure 3. An extra set of specimens was made which were finished on three different grinding lines. Each set of specimens being tested and analyzed separately. The results from the three different grinding lines are given in table 7 and shown in figure 4. The results were published by Veer et al. (2005).

Table 6: Bending strength of machine cut and ground glass, large specimens 1000 mm long and 10 mm thick, small specimens 600 m long and 50 mm wide

Width (mm)	Configuration	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
50	Lying	71.4	19.6	16
50	standing	52.4	16.1	16
125	Lying	71.0	20.1	16
125	standing	43.7	11.8	16
250	Lying	51.1	35.3	16
250	standing	39.9	24.3	16

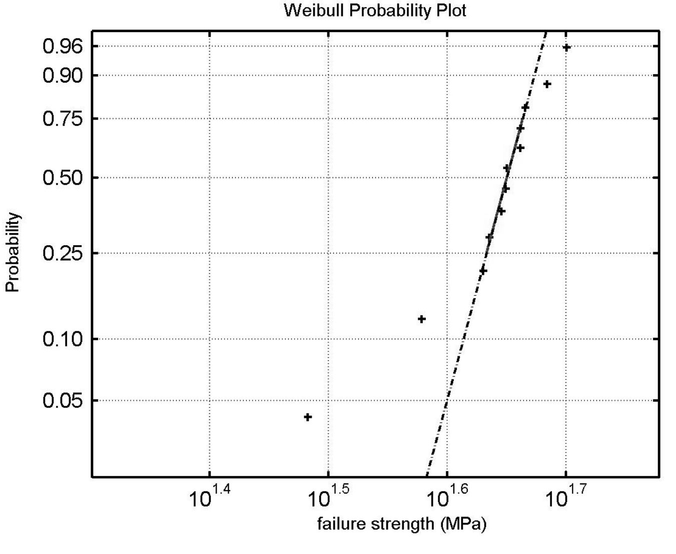


Figure 3: Weibull plot for test results of 1000×125×10 mm specimens tested standing

Table 7: Bending strength of machine cut and ground glass, specimens 1000 mm long, 125 mm wide and 10 mm thick

Grinding line	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
1	53.0	16.7	10
2	52.6	11.1	11
3	50.9	22.7	11

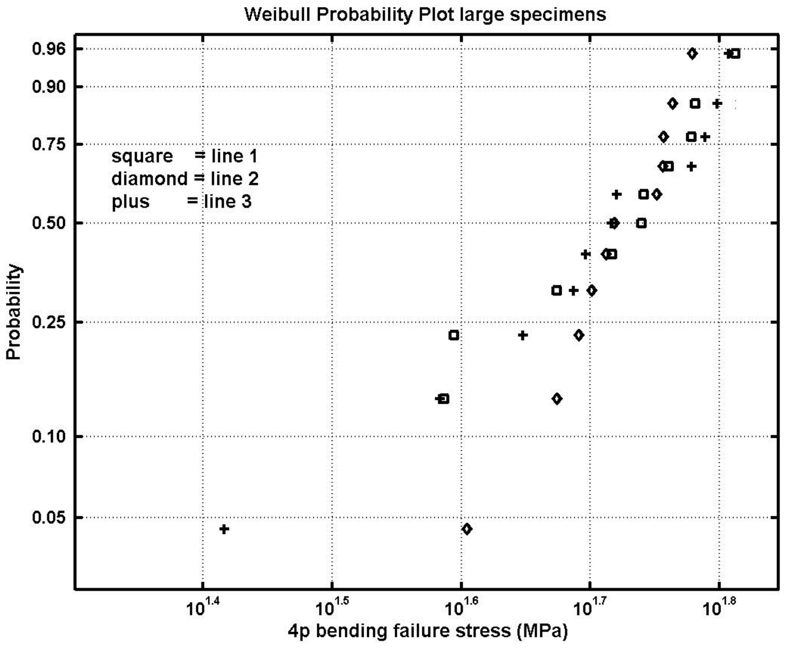


Figure 4: Weibull plot of data in Table 7

*3.6 **Results for rotary wheel cut glass***

Rotary wheel grinding is a suitable method for manufacturing small specimens as the cutting and finishing takes place in one processing step. From 8 mm thick normal glass and optiwhite glass a large number of specimens were cut. Optiwhite glass is float glass with reduced iron content and thus lacks the greenish shine of normal float glass.

Half of these were soaked in hot water at 70ºC for fourteen days. The corrosion in this period should make all flaws less sharp and thus increase the strength as stated by Gulati, (1997). The results are summarised in table 8 and shown in figure 5. These results were published by Veer et al., (2006).

Table 8: Bending strength of rotary wheel ground out specimens of length 200 mm long 20 mm wide and 8 mm thick

Glass type	Average failure stress (MPa)	Standard deviation (% of average)	Number of tests
normal	81.6	17.2	24
normal watersoaked	82.5	16.5	38
optiwhite	80.2	14.8	39
Optiwhite water soaked	83.0	13.5	38

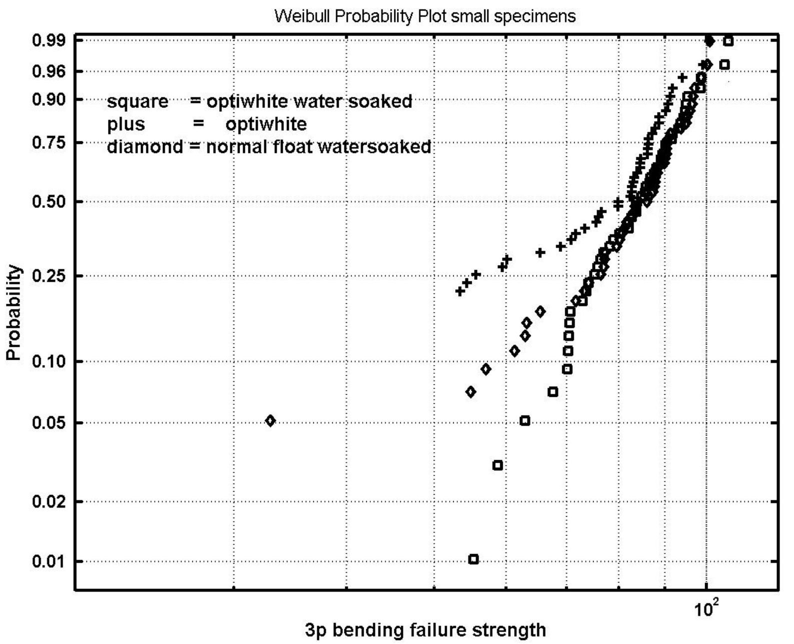


Figure 5: Weibull plot of data in Table 8

4 Discussion

4.1 Failure stress distribution

The test results cover a whole range of glass thicknesses and edge finishes. Ideally this would lead to a single value for the strength of glass. Unfortunately the enormous variance of results shows this is impossible. The problem thus resolves itself to trying to make a theory that explains these results that might lead to a value for the strength of glass.

The first step in this theory is the problem of distribution. Although it is possible to calculate averages and standard deviations for the datasets, this preassumes a normal distribution. If we take the data for the optiwhite glass from table 8, which has a large series of specimens; the histograms in figure 6 are the result. Although both sets have similar averages and standard deviation, the normal optiwhite glass does not approach a normal distribution. The water soaked optiwhite glass has a distribution closer to the normal distribution but the distribution is a-symmetric and skewed towards the lower values. Figure 5 shows a single parameter Weibull distribution for these data. Although the water soaked optiwhite glass does give an almost straight line the normal optiwhite glass shows clear bilinear behaviour. This is more typical for most of the results. The bilinear Weibull behaviour is also visible in figures 1 and 2.
The logic behind the use of the normal distribution and Weibull distribution both supposes a single causative factor with a spread in the size or effect of this causative factor. These results suggest that multiple competitive causative factors control failure in glass.
Considering the nature of glass processing this is not illogical. Figure 7 shows the edge shape of cut and of ground glass. If we look at the different places where damage can occur, there are several points where different types of damage can be introduced. Hard evidence for this is the data in table 5 and figure 2. Cut glass tested with the bur in the tensile zone has on average significantly less strength than glass tested with the bur in the compressive zone. Figure 2 also shows that even with the bur in the compressive zone some specimens have an anomalously low strength. The bur clearly has a negative effect on the strength but some specimens are apparently more damaged than others.

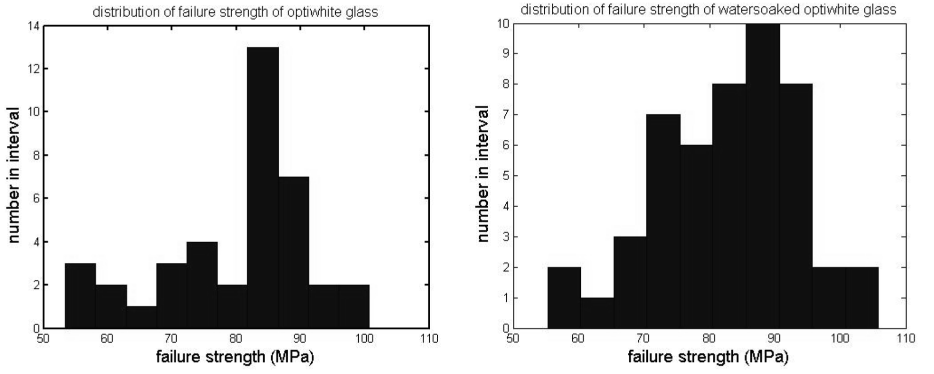


Figure 6: Histograms of failure strength of the optiwhite glass in normal and watersoaked condition

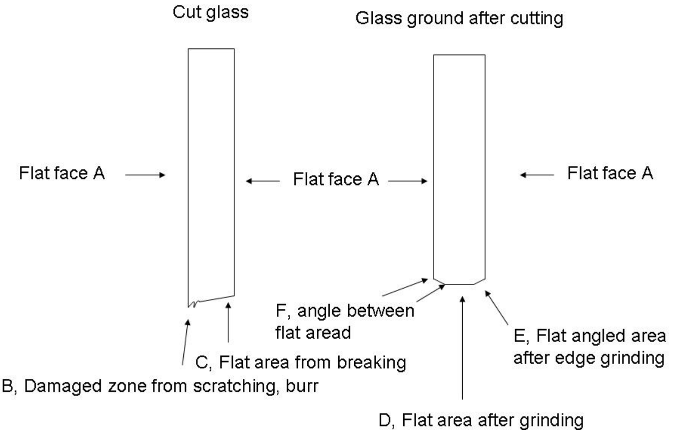


Figure 7: Schematic diagram of glass edges

4.2 *LEFM based failure criteria*

The analysis shows that the failure behaviour of glass is not solely stress based but also flaw based. The logical step is then to try to use a Linear Elastic Fracture Mechanics (LEFM), approach. This means using a combination of stress and flaw size to calculate critical stress intensities. However the results in table 6 show an LEFM approach cannot be valid. The tests in table 6 were conducted on specimens who were identically processed but with different heights/widths. All specimens were testing standing or lying in four point bending, which means that a large zone, 40% of the bottom of the specimen, is experiencing the same stress. As all specimens were identically processed by grinding after cutting they should have identical flaw distributions. The results however show the average failure stress is dependent on the height of the specimen, the lower the height the greater the strength. This implies that there is some effect of specimen stiffness or elastic strain intensity gradient on the failure process.

In any case the product of flaw size and applied stress is not constant at failure. This rules out a LEFM criterion. The anomaly of the 250 mm wide specimens tested flat can be explained by the size difference, the specimens starting to work as a plate, not as a strip.

The failure of LEFM in itself is not surprising as it is based on clearly defined cracks, not a continuous series of microscopic damage points along the different material boundaries.

4.3 *Probabilistic approach*

The solution must thus be sought in combination of stress and the distributions of flaw size and flaw shape/type. This ignores the effect of specimen height found in table 6, but this is done to reduce the problem.

If we look at the data from the standing 1000×125×10 mm specimens in figure 3, we can see that only the two lowest results deviate from the Weibull line. This is a tendency that is common in most plots. If we assume that a small minority of specimens have a more serious type of flaw, called Q, the results can be resolved. In the tests in figure 3 400 mm of the bottom edge is loaded by the four point bending to an equal stress. This means that of the 12×400 mm tested two flaws of type Q are found. This suggests that this occurs on average every 2.4 m of produced edge. The results in table 7 and figure 4 suggest that the frequency of occurrence of this type Q flaw is dependent on the grinding line. If we take the eight worst and eight best results of the 48 tests on the standing 1000x125x10 mm specimens we can make the Weibull plot shown in figure 8.

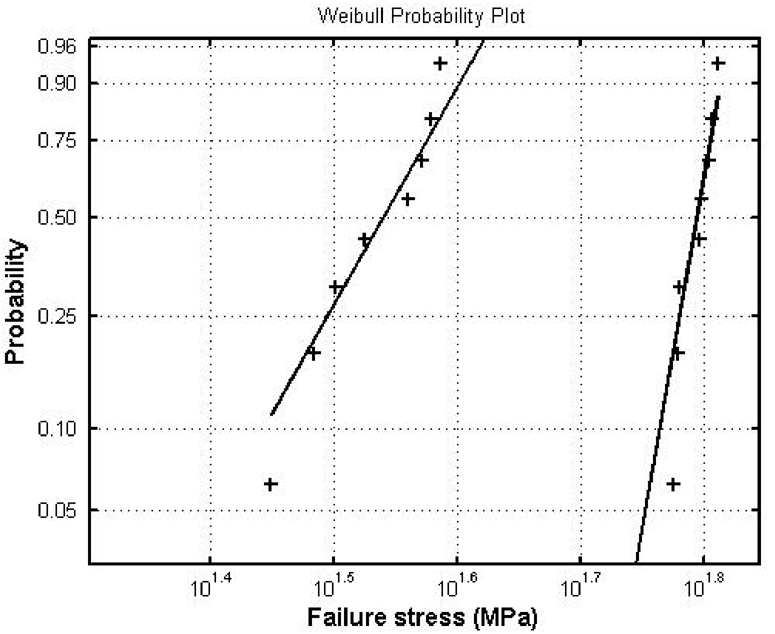
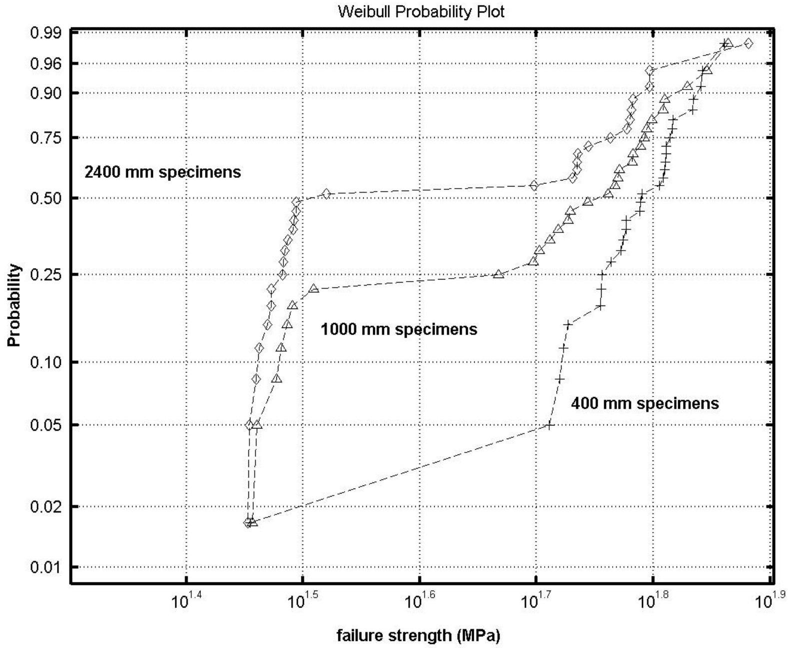


Figure 8: Weibull plot of the eight weakest and eight strongest specimens in the 1000x125x10 mm standing series

This shows quite linear Weibull behaviour for both sets, but with different moduli, suggesting the separated data belongs to two different causal populations. If we take the line of the weakest specimens a Weibull strength of 20 MPa can be calculated.

As the presence of a very small Q flaw can only be found by testing, it is almost impossible to determine its nature. For a failure stress of 50 MPa Wagener calculates using LEFM an equivalent defect size of 30µm. For 20 MPa this increases to 170 µm. In reality the edge damage cannot be described as a simple through thickness crack. It will have a three-dimensional edge crack nature. One possible cause of Q defects in cut and ground glass is that some damage produced during cutting, at Point B or C in figure 7, is not removed by grinding. The cut surface has a three-dimensional character and some flaws can be deeper than other flaws. Grinding may not remove these flaws completely as usually only the minimal amount of material is ground away. Sometimes the grinding might increase the damaging character of the flaw. The data in table 5 shows that grinding does not always increase the strength compared with cutting. In addition the glass processed by rotary wheel grinding which is not cut is generally stronger than the cut and ground glass. The absence of cutting might limit the occurrence of serious defects. This is however only circumstantial evidence at best. The results on the optiwhite glass, shown in figure 5, suggest that corrosion can change the nature of the flaws making them less severe.



With some basic assumptions we can model the predicted flaw distributions.

Figure 9: Results for statistical model for three different specimen sizes and two defect populations

If we hypothesise a randomised strength distribution around two types of defect, Q and N. Q had a distribution of one in every 2 meters of length and a failure stress of 30 MPa with a standard deviation of 7%. N has a frequency of every mm and a failure stress of 60 MPa and a standard deviation of 12 %. Using this the probabilistic four point bending failure stresses can be calculated for specimens of 400, 1200 and 2400 mm using an upper roller distance of 40% of the specimen length. Figure 9 shows the results.

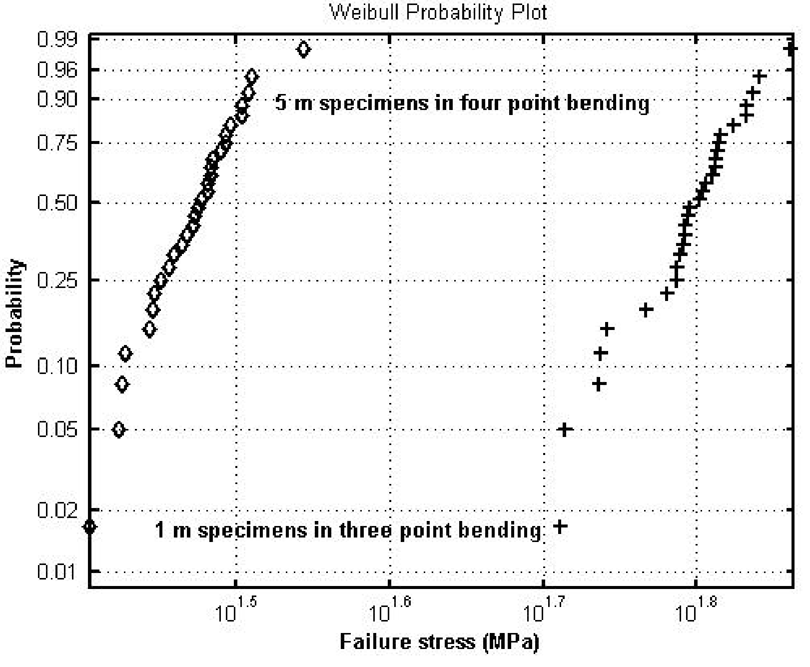


Figure 10: Predicted distributions for five meter specimens in four point bending and one meter specimens in three point bending

These results are similar to the test results. Smaller specimens have a higher failure stress result with a very occasional bad result. Large specimens show bilinear Weibull behaviour. If we change the parameters to look at large 5 meter specimens in four point bending and at one meter specimens in three point bending figure 10 results. The large specimens would show almost single Weibull behaviour corresponding with the near certainty of Q defects being present. The one meter specimens in three point bending show almost single Weibull behaviour for the N defects, as the probability of a Q defect being in the high stress zone is very low. This suggests that testing in small series and/or in three point bending will give non representative results.

4.4 Determining the strength of glass

This still leaves us with the problem of determining the strength of glass. One solution used in other materials is round-robin testing. Figure 11 combines the data of tables 5 and 6 in a single data set. This looks like it results in a single Weibull line. From this a strength of 20 MPa is calculated. This short cut is tempting. However as it has been shown that the defect distribution is dependent on the processing line and probably on the time of processing, it is mathematically wrong to combine these four data sets.

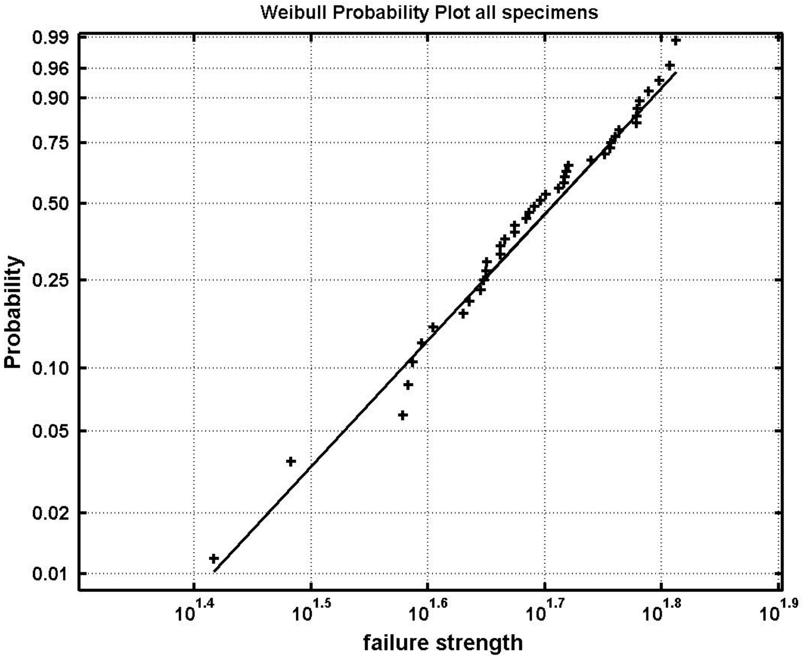


Figure 11: Weibull plot of combined data sets from tables 5 and 6

One last approach would be to look at all the data of all the sets. This shows that no specimens failed at stresses below 20 MPa. This agrees with the result found by Belis. Thus even without a mathematical description of the strength distribution; the fact that al values are greater than 20 MPa is a reasonable value as a conservative design strength. This is a result confirmed by several hundred tests. Even if the actual strength is several times greater, the 20 MPa will still be a bottom line value. The Q type defect hypothesis also implies that the larger the piece of glass, or the larger the number of pieces of glass, somewhere failure will start at a tensile stress of 20 MPa. The fact that most of the glass has not cracked at this point is not of importance from an engineering point of view, although it remains an interesting scientific problem. If we look at the other tests an upper bound value of 110 MPa can be given based on the results of the tests on the round bars and the best results of the other tests. Possibly by better control of processing this might be achieved consistently. This will be a difficult undertaking and higher values than 20 MPa can probably never be guaranteed for soda lime glass. In practice after good processing there will still be damage in handling, transport, assembly and normal use.

5 Conclusions

From the results the following is concluded:

- Failure in glass is the result of a combination of flaws and stresses
- The critical parameter cannot be described by linear elastic fracture mechanics
- The failure strength of glass can only in rare cases be described by a normal distribution.
- The failure strength can sometimes be described by a Weibull distribution.
- The deviation from the Weibull distribution is caused in industrially processed glass by a number of deviant results with low failure stresses. This is due to a rare defect that only occurs every two to three meters of edge length.
- The way the glass is processed influences the behaviour of each data set.
- Round robin testing of glass cannot give a mathematically valid result. The data sets cannot be added since they contain different flaw distributions.
- If we take the lowest values of the round-robin test sets a good Weibull plot can be suggesting a Weibull strength of 20 MPa.
- This value of 20 MPa agrees well with the minimum values of all data sets used here and is a lower boundary.
- A maximum strength of annealed float glass of 110 MPa follows from the results.

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