Bending strength of annealed, heat strengthened and fully tempered float glass

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Abstract. Although strength data for glass is available in the handbooks and reference data is given in the building norms such as the NEN 2608, the question is if these results are based on statistically significant sets of data. To determine the strength of glass in bending a large tests series of 180 specimens were prepared. These were cut from a single annealed glass plate, and identically processed on a single cutting and grinding line. One third of these were tested in the annealed condition, one third heat strengthened and one third was fully tempered. All specimens were tested in four point bending. Weibull analyses were made of the results. It is concluded that the strengths determined here are considerably lower than usually given in the literature and in the building norms. In the discussion a number of reasons for this are explained and the relevance of this to engineering is given.

Introduction

In the last two decades architectural glass has made an enormous leap from a secondary material to a material that combines structural and cladding roles. The structural role is a new and problematic one. In contrast to most other engineering materials the strength of glass is not a material parameter but a parameter dependent on processing quality and damage to the glass surface.

There is also no real agreement on how strong glass is. The concept Euronorm for structural glass has some values for the characteristic strength for annealed, heat strengthened, fully tempered and chemically toughened glass. These values have been adopted by national norms such as the Dutch NEN 2608.

There is considerable discussion in the literature whether the approach used to obtain the Euronorm values is valid. The ring on ring method used here stresses the glass surface which is of much higher quality than the edges, [1]. Alternative methods for ring on ring testing are tests where the glass is contained in a vessel which is pressurized, [2] or conventional bending tests, [3,4].

Bending tests have the advantage that they correspond closely to the tests conducted on other materials, are easily done, comparatively cheap and stress the edges of the glass. There are however significantly different results if the specimens are tested standing or lying while the aspect ratio of the specimen also has an effect, [5,6].

One problem in the literature is that most data sets are too small or it is not certain that the data sets can be directly compared. To allow accurate comparisons glass specimens of 1000×100×10 mm were prepared from a single jumbo sheet of glass and cut and ground identically on a single processing line. Of these specimens one third was fully tempered, one third heat strengthened and one third was in the original, annealed state. These specimens were tested in four point bending. Of each group of specimen half were tested standing and half lying, resulting in six groups of data.

Experimental Method

Glass beams of size 1000 mm long and 100 mm wide were cut from a single glass plate with a thickness of 10 mm. These were cut on professional automated cutting machines and finished by automated grinding and polishing. One third of the specimens were pre-stressed using full thermal tempering, one third of the specimens were pre-stressed using heat strengthening. All specimens were wrapped in PET foil for safety. For the heat strengthened and fully tempered glass multiple layers PET foil were necessary. For annealed float glass a single layer of foil was sufficient. The beams were tested in 4 point bending on a Zwick Z 100 universal testing machine with the specimen lying or standing. To avoid buckling of the standing specimens, these specimens were supported on the sides at 5 points along the length. 1mm thick Teflon sheet was used as an intermediary between the metal supports and the glass to avoid inducing high contact stresses. The test rig is shown in figure 1. A displacement rate of 1 mm./minute was used for all tests.
For a number of specimens in each series the pre-stress was measured using a scalp laser scanning device that measures the pre-stress level through the thickness. The pre-stress level was measured at the center of the specimen where the mechanical test was conducted. All specimens for which the pre-stress was determined were tested standing. It as assumed that the average pre-stress levels were representative for all specimens.

Figure 1 : Test set-up with glass specimens lying

Results

The results of all tests are summarized in table 1.

Table 1: Summary of test results

condition	orientation	Number of specimens	Average failure stress in four point bending (MPa)	Standard deviation (% of average)	Average pre-stress (MPa)	Standard deviation (% of average)	Calculated Weibull strength (MPa)
annealed	Lying	24	42	21.8%	-4.5	37%	24
	Standing	30	27.5	20.1%			20
heat strengthened	Lying	23	104.0	27.7%	-64.3	3.8%	54
	Standing	29	71.3	15.8%			52
fully tempered	Lying	25	154.4	18.9%	-100.6	12.9%	88
	Standing	32	98	13.7%			77

Annealed glass

A Weibull plot of the results for annealed glass is given in figure 2. The values for the lying glass are given as diamonds and for the standing glass as plusses. The specimen failed by simple cracking as shown in figure 3. Higher failure stresses result in more cracks and more crack branching. Although the results of the lying tests suggest a reasonable Weibull fit, figure 2 suggests that both data sets are bilinear.

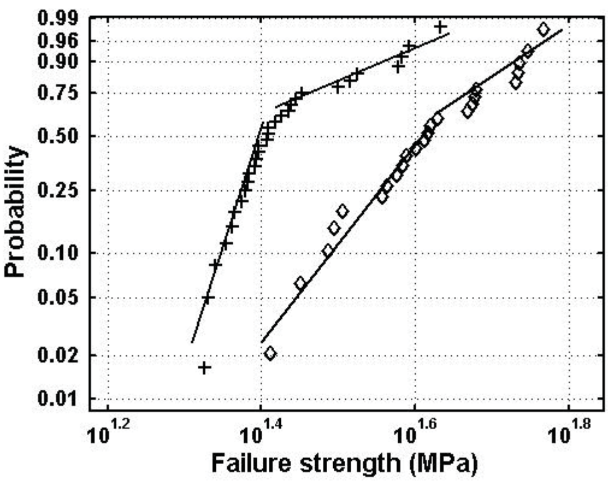

Figure 2: Weibull plot for annealed glass tests

Figure 3: Failure pattern of annealed glass tested lying, failing at 55.8 MPa

Heat strengthened glass

A Weibull plot of the results for heat strengthened glass is given in figure 4. The values for the lying glass are given as diamonds and for the standing glass as plusses.The specimen failed by simple cracking from the edges, followed by secondary cracking resulting from the release of the pre-stress, as shown in figure 4. The heat strengthened glass consistently fragmented into fragments of about 2 to 3 cm length on average. This suggests a rather high pre-stress level for heat strengthened glass. Specimens that fail at higher bending stresses do not fragment into smaller pieces. Figure 4 suggests that both data sets are essentially bilinear in their Weibull behavior.

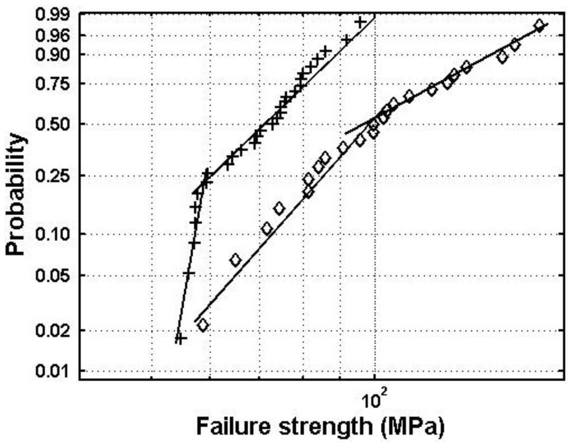

Figure 4: Weibull plot for heat strengthened glass tests

Figure 5: Failure pattern of heat strengthened glass tested lying, failing at 111.7 MPa

Fully tempered glass

A Weibull plot of the results for fully tempered glass is given in figure 6. The values for the lying glass are given as diamonds and for the standing glass as plusses. The specimen failed by simple cracking from the edges, followed by massive cracking resulting from the release of the pre-stress, as shown in figure 7. The fully tempered glass consistently fragmented into fragments of less than one cm length on average. The specimens that fail at lower bending stresses do not fragment into larger pieces. In contrast to the results for annealed and heat strengthened glass the Weibull behavior for the standing glass is reasonably linear, although there is a small hump in the Weibull plot of the lying glass. This is caused by clustering of data at a certain stress level.

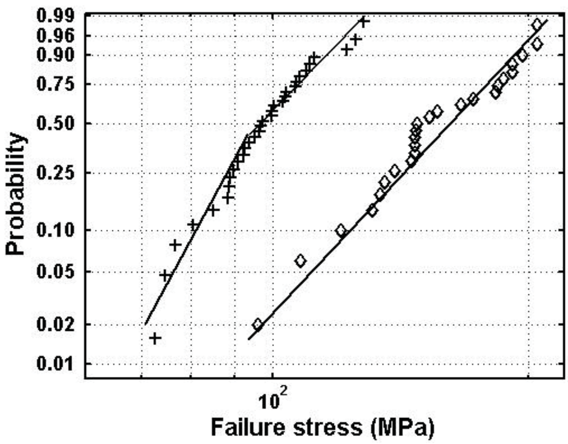

Figure 6: Weibull plot for fully tempered glass tests

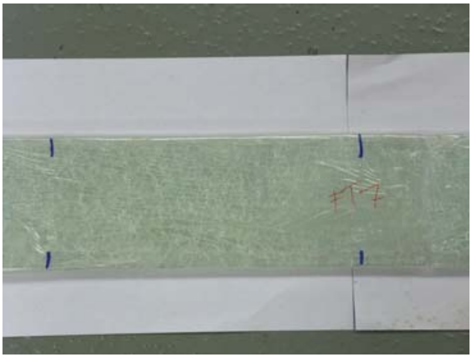

Figure 7: Failure pattern of fully tempered glass tested lying, failing at 107.7 MPa

Failure stress in relation to pre-stress

For a limited number of specimens the pre-stress through the thickness was measured using a scalp laser pre-stress measuring device. Measurements of the center section were made. And the average pre-stress on the surfaces was calculated. These specimens were tested standing. A plot of calculated failure stress against measured pre-stress is given in figure 8. The pre-stress measurements are quite reproducible. The general accuracy is about ± 5 MPa. An interesting point is that the measured pre-stress levels are well below those generally quoted. For heat strengthened glass a value of -100 MPa is commonly given which contrasts with the measured value of -64.3 while for fully tempered glass a value of -200 MPa is commonly given which contrasts strongly with the measured value of -100.6.

It should be noted that the fragmentation pattern in these tests was fully consistent with that observed before and illustrated in figures 3, 5 and 7.

The relatively high standard deviation in the measured pre-stresses annealed float glass should be looked at in terms of the experimental accuracy of the measurement which is in the same range as the average measured value.

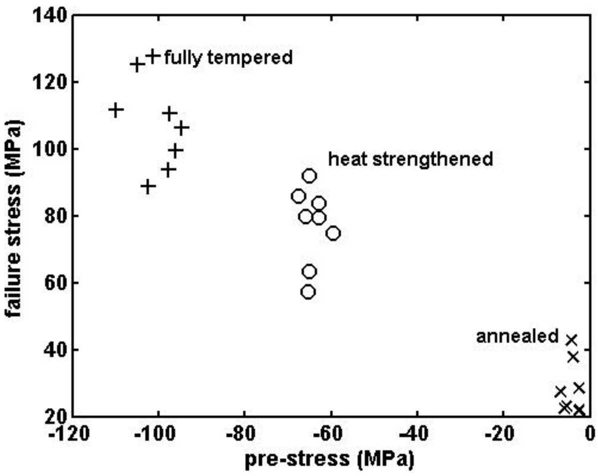

Figure 8: Relation between pre-stress and failure stress.

Discussion

From an engineering point of view the ideal result would be a simple formula to calculate the strength of glass for any condition. The results make it clear that no simple solution exists. The results show clearly that the strength of glass is not only dependent on the orientation of the glass versus the load, clearly other aspects such as aspect ratio also play a role. Even a large number of identical specimens tested identically do not give a unique result.

The results show considerable spread which cannot be described easily by normal statistics. The commonly used Weibull approach was found to be only valid for fully tempered glass. As the Weibull function cannot describe the behavior of annealed or heat strengthened glass adequately the validity of the underlying model for glass has to be questioned. Assuming that the lower strength values can be used to provide calculate a safe Weibull modulus a 1 in 1000 failure probability can be used to calculate the Weibull strength values as given in table 1. These should not be used as design values as standing specimen with higher aspect ratios than used will result in a lower Weibull strength. The given values are only to allow comparison between the six sets of data.

More interesting is the underlying problem of the material mechanics involved. The results indicate that a lot of our understanding about the failure of glass is incorrect. The consistent bi-linearity of the Weibull plots implies that there is no single source of failure. More important is the non-correlation between failure strength and fragment size of heat strengthened and fully tempered glass. Half of the heat strengthened glass is stronger that the weakest fully tempered glass specimen. This half however consistently gives larger fragments of consistent size. The low strength fully tempered specimens fragment consistently to small fragment of consistent size. Fragment size is thus a good indicator of the pre-stress that has been introduced, but no indicator of strength. The pre-stress level itself is thus also no indicator or guarantee of failure strength.

As the pre-stress level is consistent within a series the large variation in strength implies that failure cannot be started by the simple concept of √(defect size)×(applied stress+pre-stress) gives a stress intensity that is greater than the critical one. The commonly accepted principle that failure stress = applied stress – pre-stress is also shown to be false. As a general statistical result this might approximately hold for glass tested lying, as the results in table 1 show. This is clearly not true for the results of the standing experiments. In several cases the individual failure stress is smaller than the measured pre-stress.

The lying annealed glass has a failure stress range from 25 to 60 MPa. The lying heat strengthened glass has a failure stress range from 60 to 170 MPa. The variations in failure stress are about three to four times the variations in pre-stress levels for heat strengthened and fully tempered glass. This implies that the failure behavior of heat strengthened and fully tempered glass is still controlled more by the combination of material behavior/flaw type/flaw size distribution than by the pre-stress level.

Conclusions

From the results it is concluded:

- The Weibull descriptor is only valid in certain cases as descriptor for the failure strength of glass.
- For certain cases a certain guaranteed minimum strength can be defined. This is however dependent on edge quality, orientation of glass relative to load, aspect ratio and pre-stress level.
- Fragment size after failure is a good indicator of the pre-stress level. However it is no indication of the strength of the glass.
- The physical process of the failure of pre-stressed glass is not controlled by the combination of defect size and the sum of the applied stress and (negative) pre-stress.
- The failure strength is not the sum of average intrinsic strength plus pre-stress level. In certain cases the glass fails at an applied load which is smaller than the pre-stress level.
- Research is needed into the consistency of pre-stress levels.
- Without a better understanding of the physics of glass failure, it will not be possible to create an adequate statistical descriptor of the failure strength.

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