STRENGTH AND FRACTURE BEHAVIOUR OF ANNEALED AND TEMPERED FLOAT GLASS

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ABSTRACT

Glass is a material that is strong in compression but has widely varying strength in tension and fractures uncontrollably. The results that are reported in the literature vary widely. Reliable data about the strength of annealed and tempered float glass are scarce. 4 point bending tests have been conducted on annealed and fully tempered float glass panels of two different sizes. The tests were done with the panels in a standing position rather than the more common lying position. The results show that the design strength of tempered glass is much less than commonly assumed. Failure in both types of glass starts at defects in the tensile zone. The amount of crack branching correlates well with the strength of the glass. In tempered glass cracks first grow from the defect that initiates failure. The decohesion of the tempered glass into little fragments follows after the panel has already failed.

1 INTRODUCTION

Glass is a material that is used in all branches of engineering because it is the only rigid transparent material available. The last decades have seen increasing use of glass in automobiles and buildings. The tendency in modern buildings to increase the amount of glass used has resulted in the desire to use the glass in a load bearing manner. Glass however is a brittle material that fails unpredictably in tension. Although the strength of glass can be described by Weibull statistics and probabilistic strengths calculated, as shown earlier by Veer and Zuidema [1,2], considerable uncertainty exists in the literature about the exact parameters and the allowable design strength. For this reason 4 point bending tests have been conducted on standing glass panels of 1000×250 mm and 1000×125 mm using annealed float glass and fully tempered float glass.

2 EXPERIMENTAL METHOD

Glass beams of size 1000 mm long and 125 or 250 mm wide were cut from a single glass plate with a thickness of 10 mm. These were professionally cut on professional cutting machines and finished by grinding and polishing. Half of the specimens were pre-stressed using full thermal tempering. All specimens were wrapped in PET foil for safety. For annealed float glass a single layer of foil was sufficient, for tempered float glass three layers of foil were needed.

The beams were tested in 4 point bending on a Zwick Z 100 universal testing machine with the specimen standing. The cut and processed edges were thus directly stressed. To avoid buckling the specimen was supported on the sides at 5 points along the length. 2 mm thick sheet nylon was used as an intermediary between the metal supports and the glass. The test rig is shown in figure 1.

A problem arose with the 250 mm high tempered glass specimens. The forces involved induced failure by local crushing of the glass at the loading rolls in some cases, followed by disintegration of the specimen as the pre-stress became unstable. Thus a considerable number of these specimen did not provide acceptable results.

For the annealed float glass specimens the number of cracks that originate from the point of failure were counted. For the tempered glass specimens the decohesion of the specimen that is caused by the release of the pre-stress makes introduces such errors that the number of cracks originating form the point of failure were not counted.

Figure1 : Experimental setup

3 RESULTS

The results for the 125 mm high specimens are summarized in table 1. The results for the 250 mm high specimens are summarized in table 2.

Table 1: test results for 125 mm high specimens

Test number	σ_f annealed float glass 1000×125 mm (MPa)	Number of branched cracks	σ_f tempered float glass 1000×125 mm (MPa)
1	37.9	14	105.9
2	44.6	28	107.1
3	46.3	27	110.5
4	50.2	32	148.8
5	48.3	28	146.3
6	43.2	26	149.9
7	45.9	26	146.9
8	42.7	23	155.3
9	44.2	21	138.0
10	44.7	25	156.7
11	30.4	12	149.2
12	45.9	26	166.9
Average	43.7		140.1
Standard deviation (%)	11.8		14.8

4 DISCUSSION

The data is plotted in Weibull diagrams and normal probability plots in figures 2 to 5. Although earlier research by Veer and Zuidema suggested that the failure behaviour of glass could be described by Weibull statistics these results suggest that this conclusion is not valid in all cases. Of the specimens tested only the 250 mm high annealed float glass specimens approach a reasonable Weibull distribution as is shown in figure 4. In practice most of the data sets cannot be described

Table 2: test results for 250 mm high specimens

Test number	σ_f annealed float glass 1000×250 mm (MPa)	Number of branched cracks	σ_f tempered float glass 1000×250 mm (MPa)
1	39.4	5	96.2
2	21.9	11	122.2
3	28.0	17	95.6
4	49.8	47	64.8
5	48.8	47	67.1
6	45.2	47	80.7
7	50.3	50	91.9
8	27.6	15	
9	45.9	35	
10	37.6	34	
11	47.0	48	
12	36.9	11	
Average	39.9		88.4
Standard deviation (%)	24.3		22.3

fully by either the Weibull or the normal distribution. Considering the spread in results this implies design strengths of 25 MPa and 80 MPa for the 125 mm high annealed respectively fully tempered float glass. For the 250 mm high specimens this would 16 and 50. This values are significantly lower than those assumed in the relevant design standards (3). The values in these design standards are based on experiments with the glass lying. It has been noted by Hess, (5) that glass tested standing has a strength about 40% less than that tested lying. These result suggest that the fall in strength can be greater than 40% and is also dependent on specimen size.

No clear direct reason for the failure of the Weibull distribution is evident. The most logical and simple explanation that there are several types of failure mechanism, possibly associated with different types of defect causing the initial failure. The specimens that fail at lower strength values having some rare type of defect. Fractographic analysis so far has not provided any evidence for this theory. This theory would however explain some of the anomalous data found earlier by Veer and Zuidema (1,2) and which is also shown in the design standards (4). The small size of critical defects in glass and the transparent nature of glass make it difficult to study the edges and fracture surfaces.

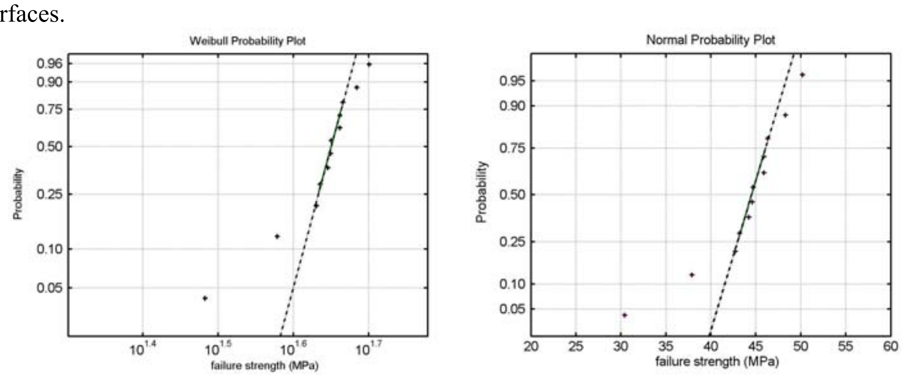

Figure 2: Weibull and normal probability plot for annealed float glass 1000×125 mm

The cracks generally show up in a fan shaped form emanating from the point in the tensile zone where fracture started. This fan shaped pattern is visible in both annealed and tempered float glass, as can be seen in figures 6 and 7. The presence of the fan shaped pattern in tempered float glass is actually contrary to what is commonly stated in the literature, (3). Tempered glass is supposed to disintegrate immediately on overloading. In the lying condition which is normally used for testing no special crack pattern can be distinguished. In the standing position used in these tests the fan shaped crack pattern implies that failure in tempered glass is caused by the overloading of edge defects similar to those in annealed glass and that the cracks causing this failure run at such a high speed that the specimen fails before it disintegrates due to the release of the pre-stress energy. The unstable cracks from the overloading must thus be significantly faster than the cracks causes by the release of the pre-stress.

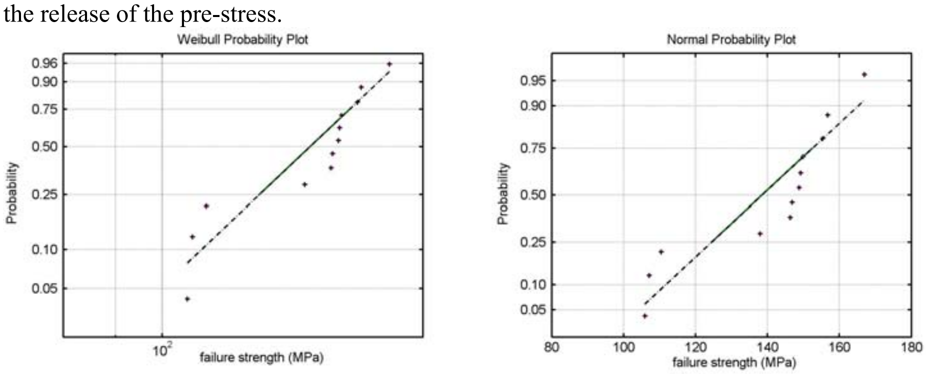

Figure 3: Weibull and normal probability plot for fully tempered float glass 1000×125 mm

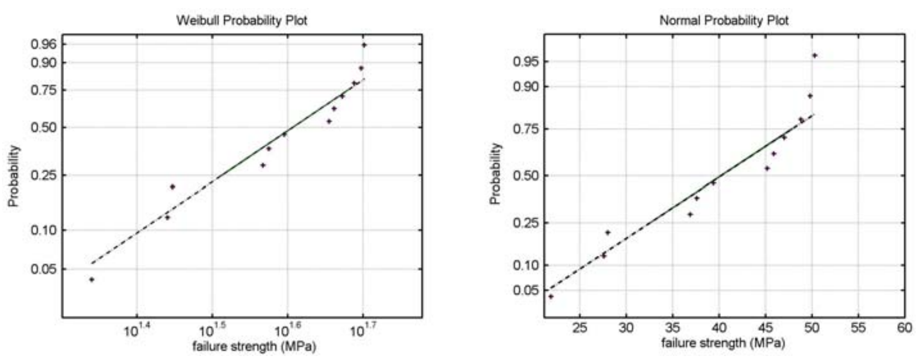

Figure 4: Weibull and normal probability plot for annealed float glass 1000×250 mm

In the literature, (3,6), a relationship is usually assumed between the number of cracks in glass and the stress at failure. In figure 8 and 9 the number of cracks in the fan shaped area of the annealed float glass specimens has been plotted against the failure strength. For the 125 mm high specimens all data falls in a linear relation, for the 250 mm high specimens most of the data falls in a linear relation. This implies that there is a relation between the number of cracks in the fan shaped area and the failure stress. The data for the 250 mm high specimens shows that there can be exceptions to this rule. Assuming a low failure stress from the fractographic evidence can thus be wrong in certain cases, although as a general rule it seems to be valid.

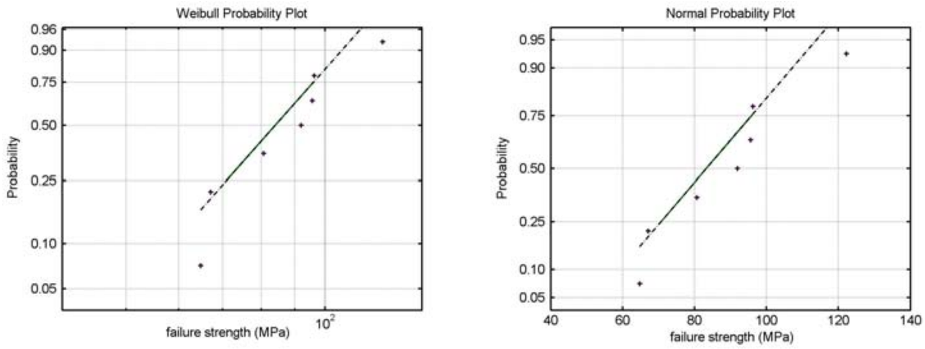

Figure 5: Weibull and normal probability plot for fully tempered float glass 1000×250 mm

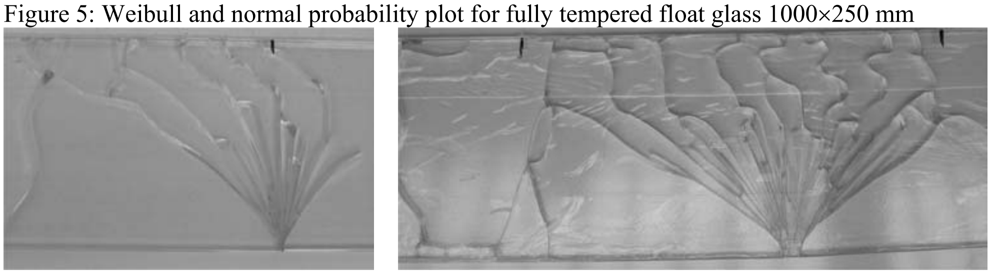

Figure 6: crack pattern in weakest and strongest 125 mm high annealed float glass specimens

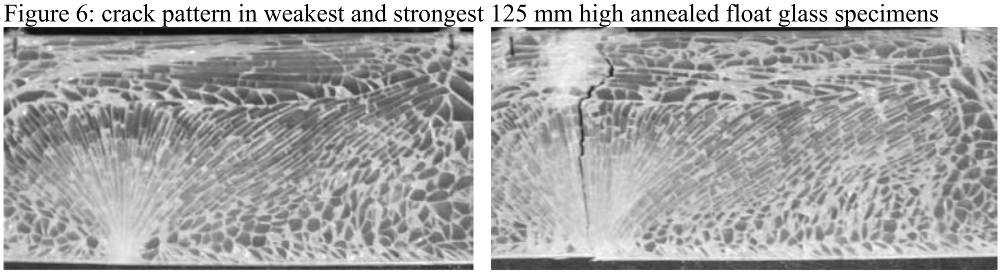

Figure 7: crack pattern in weakest and strongest 125 mm high tempered float glass specimens

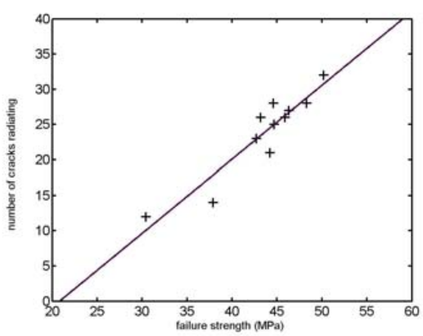

Figure 8: cracks branching from point of failure for 125 mm high glass

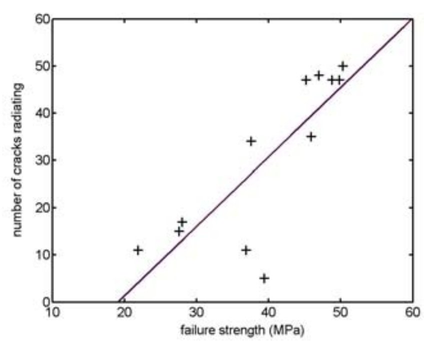

Figure 9: cracks branching from point of failure for 250 mm high glass

5 CONCLUSIONS

From the results the following is concluded that :

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- The failure strength of 125 mm high annealed float glass and tempered float glass do not fit the Weibull distribution function.
- The deviation from the Weibull distribution is especially significant at the bottom of the failure strength distribution
- The results suggest that this deviation can only be explained by the presence of multiple failure mechanisms with different probability distributions
- The design strengths of glass beam specimens tested standing is significantly lower than that reported in the literature
- The failure of tempered glass specimens tested standing is by crack growth from an initial defect. Only after the specimen has failed by overloading does cracking due to the release of the pre-stressing energy take place
- There is a good correlation between the number of cracks that develop from the point of failure and the failure strength
- In some cases there are significantly fewer cracks than would be expected from the failure stress
- The relation between the number of cracks that develop and the failure stress is thus not an absolute indicator of the failure stress

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