Bending Strength and Failure Behaviour of Welded Borosilicate Glass

F.A.Veer[&], C. Giezen[&], F.P. Bos[&], P.C.Louter[&], A.C.Riemslag*

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

* Delft University of Technology, Faculty of Materials, Maritime and Mechanical engineering

f.a.veer@tudelft.nl

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Abstract. Borosilicate glass is extensively used in laboratories and in the chemical industry because it can be welded to form seamless glass work. The extensive use of glass in modern architecture has led to the question if welded borosilicate glass can be used to manufacture structural components.

To study this problem three types of specimens have been manufactured and tested in single bending and 4 point bending tests. The failure stresses have been determined and the types of crack that have developed have been analysed. The strength results have been analysed using Weibull statistics.

The results show that the weld has a strength which depends on how the load is applied. The Weibull strength is 20 MPa in the worst loading case and 50 MPa in the best loading case. The Weibull strength of the mother material is 65 MPa. The results indicate that there is no effect of the heat affected zone. The weld itself is usually the point where cracks originate.

Introduction

Glass in architecture is conventionally connected using bolts or using adhesives. Bolted connections require use of tempered glass which is easily damaged. Adhesives are generally not allowed in structural systems without a mechanical backup. In addition there are questions about the long term stability of adhesive systems under UV degradation and environmental attack.

Welding glass is another possibility. Welding borosilicate glass is comparatively easy and has long been used to manufacture laboratory glass. Some attempts have been made to weld conventional soda lime glass but the residual stresses introduced are a problem, [1].

The tubular and rod shapes in which borosilicate glass is supplied, [1], lend themselves to structural shapes while the low thermal expansion coefficient of the borosilicate glass minimizes residual stress development during cooling. As a result an exploratory research program was started to look at the suitability of borosilicate glass for structural components.

Designing specimens

As a casus a glass truss based on welded shapes was designed. This is shown in figure 1.

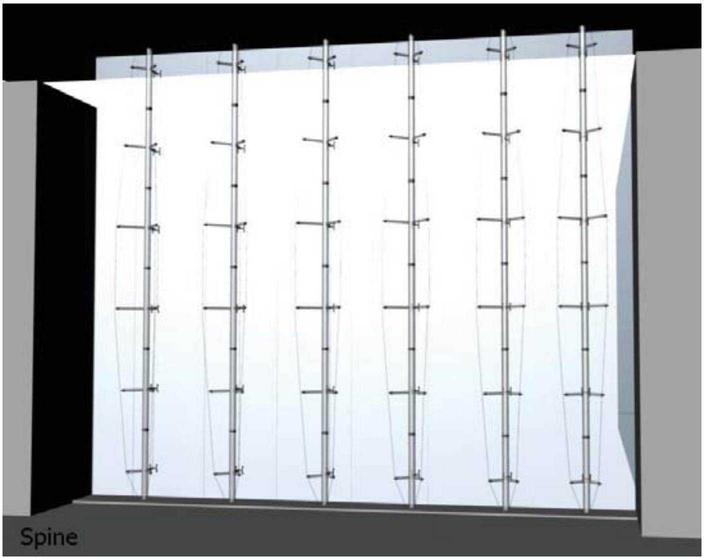

Figure 1: Glass truss design

From this design a number of specimen geometries and three forms of test were developed, four point bending, compression and moment. These are illustrated in figures 2, 3 and 4. All geometries were modelled in the DIANA finite element package to determine the applied force, local stress relation.

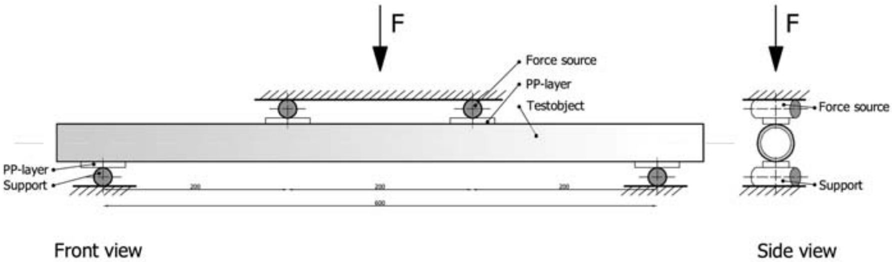

Figure 2: four point bending specimen

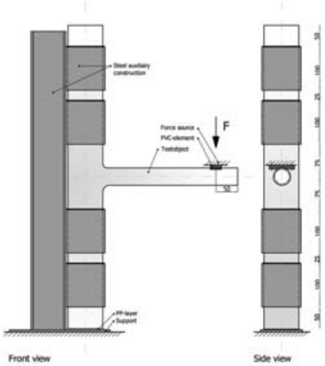

Figure 3: Moment test

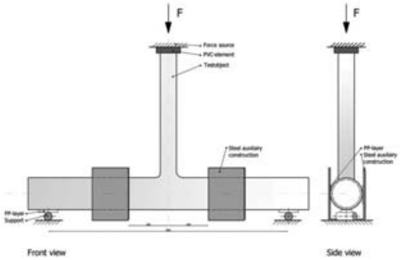

Figure 4: Compression test

Experimental method

Specimens were manufactured by a professional glass welding firm. The necessary supporting jigs were manufactured. Tests were conducted using a Zwick Z-100 using a displacement rate of 0.5 mm/minute. Of each series two specimens were instrumented using strain gages to compare measured strains with the finite element predictions. A typical test setup is shown in figure 5.

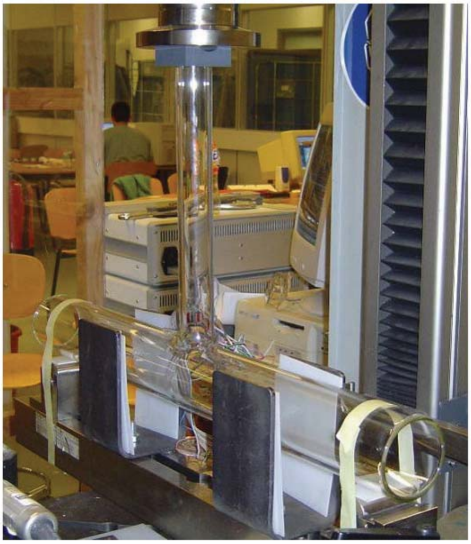

Figure 5: test setup

Results

The results for the three series are given in tables 1, 2 and 3. The failure stresses were calculated using analytical solutions. The Weibull plots of the failure stresses are given in figures 6, 7 and 8. The results seem similar in size and spread to those of conventional glass as given by Veer [3].

Table 1: Results of four point bending tests

Test number	Failure stress (MPa)	Test number	Failure stress (MPa)
1	44.7	12	68.1
2	23.1	13	68.7
3	65.6	14	67.7
4	83.9	15	64.7
5	78.9	16	92.1
6	76.1	17	52.8
7	61.0	18	65.8
8	53.4	19	24.9
9	82.1	average	62.8
10	50.9	Standard deviation (% of average)	28.9
11	68.2		

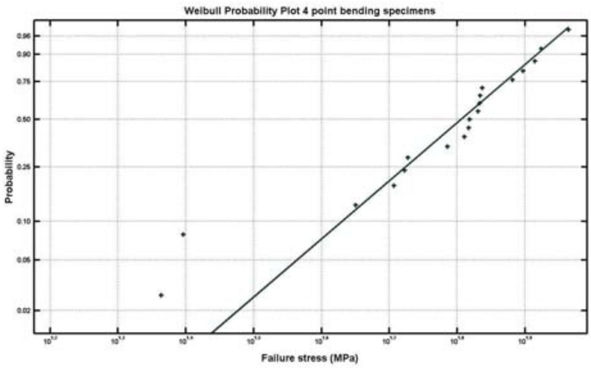

Figure 6: Weibull plot of 4 point bending tests

Table 2: Results of compression tests

Test number	Failure stress (MPa)
1	32.6
2	44.6
3	52.6
4	56.9
5	52.4
6	53.4
7	46.5
8	62.4
Average	50.2
Standard deviation (% of average)	17.8%

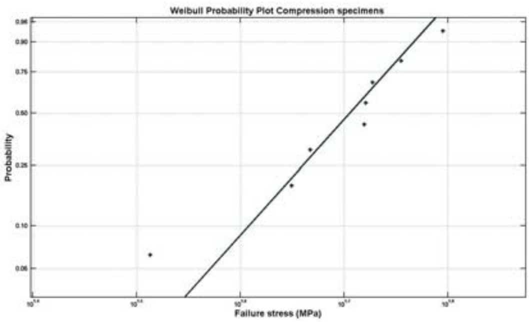

Figure 7: Weibull plot of compression tests

Table 3: Results of moment tests

Test number	Failure stress
1	64.9
2	66.2
3	74.1
4	73.3
5	85.3
6	72.1
7	70.4
8	81.1
9	71.7
10	70.9
Average	73.0
Standard deviation (% of average)	8.5%

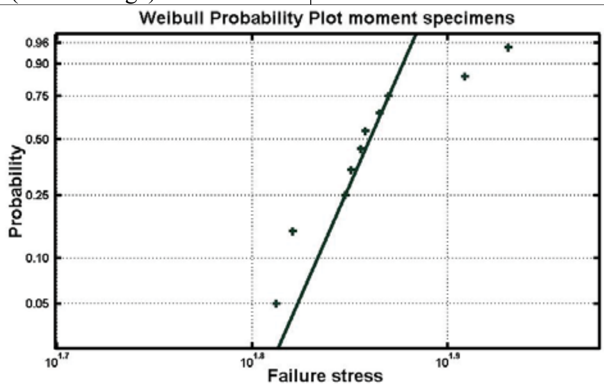

Figure 8: Weibull plot of moment tests

Comparison of strain gages and finite element prediction

All test geometries were modelled in the DIANA finite element package. Of each series two specimens were instrumented using strain gages. This mainly as the unusual T geometries used need to be validated as there is little experience with these specimens in glass. Examples are shown in figures 9 and 10. The correspondence between strain gages and FEM prediction was quite good.

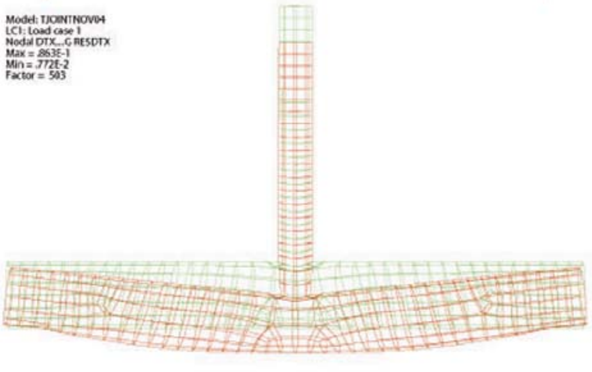

Figure 9: FEM model of compression test

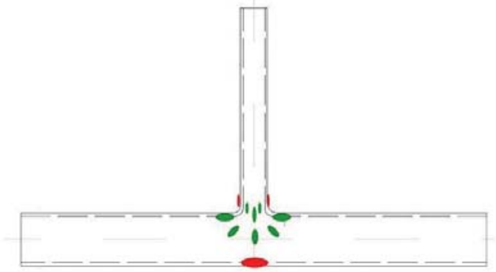

Figure 10: Strain gage result of compression test

Failure modes

Important is the failure mode of the specimens. For the tube specimens tested in four point bending there were five distinct modes of failure which are shown in figure 11. Only specimen started failure outside of the zone between the upper rollers. All other specimens failed in the weld (7 specimens), in the heat affected zone (8 specimens) or in the original tube material (three specimens). There is no clear preference and no indication of any relation between location of failure and failure stress. This implies that in Welded borosilicate glass there is no significant difference between the weld, the heat affected zone and the mother material.

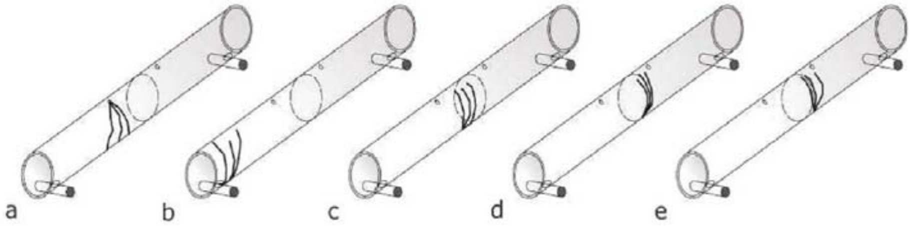

Figure 11: Failure modes of 4 point bending specimens,

a failure at roller
b failure at support
c failure in mother material
d failure in weld
e failure in heat affected zone

In the compression tests three modes of failure were found, which are shown in figure 12. At the supports (six specimens), in the non welded tube at the bottom (1 specimen) and at the weld (1 specimen). This implies that this type of specimen was not really suitable and gives no good results. At best these results show again that there is no significant difference between weld, heat affected zone and mother material in terms of strength.

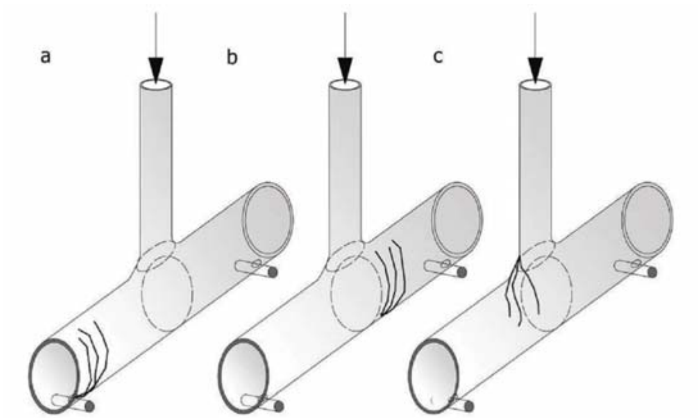

Figure 12: Failure modes of compression specimens

a failure at the support
b failure at the un-welded tube at the bottom
c failure at the welded joint

For the moment test specimens only a single failure mode was found, shown in figure 13. All failures started in the heat affected zone which is also the point of maximum stress. The failure stresses seem to be significantly higher than for the 4 point bending specimens.

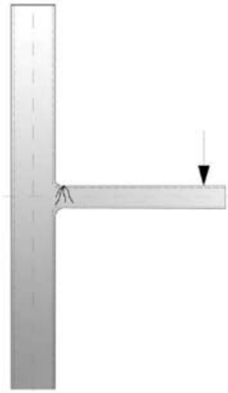

Figure 13: Failure mode of moment specimens.

Conclusions

From the results it is concluded that:

- the strength of welded borosilicate tubes is comparable to the strength of un-welded tubes
- there is no preference between failure at the weld, heat affected zone or mother material
- there is considerable scatter in the strength data
- the data cannot completely be described using a Weibull distribution
- a minimum value for the bending strength of 20 MPa seems to be a reasonable assumption

Literature

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The strength of glass, a non transparent value
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