Improving the engineering strength of heat strengthened glass

F.A.Veer [1], Y.M. Rodichev [2]

[1] Delft University of Technology, the Netherlands

[2] Pisarenko Institute of Strength, Kiev, Ukraine

Although glass is increasingly used as a structural material, glass is not produced to strength standards, like steel and concrete. Of the three types of glass: annealed, heat strengthened and fully tempered, only heat strengthened glass has the properties to function as a safe structural material. These properties are strength, resistance to stress corrosion cracking, and controlled fragmentation. In this paper the factors controlling the strength of heat strengthened glass are assessed. The dominant influence is the spread in compressive pre-strength. Opportunities for quality control of the compressive pre-strength are analysed using experimental results. The consequences for the predictability of the strength and the requirements for quality control are discussed.

Key words: Glass, strength, tempering of glass, design strength

1 Introduction

For a structural engineer the strength of a material is critical to the design. When working with steel, the design strength is already expressed in the steel description: S235 being a steel with a minimum yield strength of 235 MPa. Working with concrete, C25 is a concrete with a minimum compressive strength of 25 MPa after 28 days. Of both these materials the quality is tested continuously. Steel gets tested at several points of the production process, while of each concrete batch, specimens are made and tested after 7 and 28 days of curing. The structural engineer who works with float glass can only choose annealed, heat strengthened and fully tempered. Chemically strengthened glass is usually too expensive for architectural applications. The description of the glass thus only describes the heat treatment. Additionally, the laminating foil can be specified and the layers of glass in the laminate. None of these parameters deal with design strength, at best only with residual strength. In the codes, values for the characteristic strength of glass are given [1]. In table 1 these values are compared with previous results of the authors. Clearly, the characteristic strength is not characteristic for the minimum or average of the data from experimental results such as those given in [2]. In itself this is not a problem for safe design, since the code also prescribes the use of multiple partial safety factors - more completely explained by Badalassi et al. [3]. These partial safety factors effectively guarantee that no excessive stress is applied to the material. It does however raise the question of the value of the characteristic strengths given in [1]. Certainly these values are less precisely defined calculation factors than the 235 MPa yield stress of S235 steel or 45 MPa compressive failure stress of C45 concrete. As glass is, produced under well-defined measurable conditions, just as steel or concrete, proper quality control should be able to assign it a characteristic strength.

In fact, the glass industry does not conduct quality control checks on the mechanical properties of glass. Extensive quality control checks exist for transparency and inclusions [4]. These, however, have never been related to the mechanical properties, which probably might not be possible at all.

The question thus arises whether quality control can guarantee the mechanical properties. This paper will look into the problems of such in heat strengthened glass. This, as annealed glass is sensitive to stress corrosion cracking while fully tempered glass on failure disintegrates, thus having limited residual strength even when laminated [5]. Laminated heat strengthened glass is the only glass type suitable as a structural material as it combines stable strength with some residual strength and some damage tolerance.

Table 1. Characteristic strength of glass as given in [1] and some test results of the authors (MPa)

Type of glass	Annealed	Heat strengthened	Fully tempered
Characteristic strength [1]	45	70	120
Minimum in beams tested with failure on edge [2]	21.2	54.9	72.6
Minimum in plates tested flat [2]	25.8	58.8	96.1
Average in beams tested with failure on edge [2]	27.5	71.3	98
Average in plates tested flat [2]	42	104	157.4

2 The strength of heat strengthened glass

Glass is a brittle material failing by unstable crack propagation from a flaw exposed to too high tensile stress. The failure process can be described using Linear Elastic Fracture Mechanics extended to allow for stress corrosion cracking. In essence glass fails when somewhere in the glass the following condition is met:

$$c\sigma\sqrt{\pi a} \geq K_{IC} \quad (1)$$

where c is a geometrical correction factor for the finite size of the specimen, σ the local tensile stress at right angles to the plane of the defect, a the size of the defect and K_{IC} the fracture toughness of the glass. In annealed glass the local tensile stress is only the result of the applied stress. In tempered glass the applied stress and the residual pre-stress can be added using the principle of elastic superposition, although as these are vector quantities it is necessary to look at the direction of the local stresses. A compressive pre-stress thus effectively decreases the local tensile stress by subtracting from the applied stress. Theoretically this equation has three variables

- defect position and relative size (c)
- defect size (a)
- compressive pre-stress, (σ_r)

The effect of defect position is minor [6]. As the cracks are small and sharp, c will be almost constant. The variations in defect size a can only be determined by analysing the strength of a large quantity of significantly varying annealed glass panels. In an extensive study by Overend and Louter [7], the strength of some 350, 3 mm thick glass specimens, both new and weathered, were determined using ring on ring tests. As this type of test loads the glass bottom surface and not the edges the glass quality and test results are statistically more consistent. If the edges are loaded, the scatter is greater due to the greater quality differences at the edges as shown by the authors [8]. Overend and Louter found that for new annealed glass this gave a 0.8% fractile strength of 71.8 MPa while for weathered glass this was 18.7 MPa. The new annealed glass had failure strengths of about 80 to 160 MPa and the weathered glass had a strength range of about 30 to 100 MPa. Assuming K_{IC} = 0.55 MPa√m and c = 1.12 this implies defects of a maximum 0.085 mm for the weathered glass to 0.003 mm for the strongest fresh glass. Defects of this size are difficult to determine optically in a transparent material. At the edges lower strengths down to 20 MPa can be found, corresponding to defects of 0.15 mm. Even these defects are difficult to find by optical inspection.

Weathering, although critical for annealed glass, however has limited effect on the strength of tempered glass as demonstrated by Morse et al. [9]. All exposed glass will be scratched by sand and other hard particles, irrespective whether it is annealed or tempered. The compressive surface pre-stress prevents stress corrosion from mechanical damage that occurs during service life. Blunt scratches thus are not converted into sharp cracks as will happen in annealed glass. In annealed glass used in windows, a local temporary tensile stress will occur repeatedly due to wind pressure. This over time will cumulatively provide enough time for stress corrosion to act. In tempered glass this cannot occur, so weathering has a limited effect on the strength.

The consistency of the failure strength of heat strengthened glass, thus depends on the defects present in the annealed glass at the moment of tempering and the variation of the compressive surface pre-stress induced by the tempering. As these are currently not measured during production, there is no quality control on them during production. In addition, even if surface and edge defect quality during production would be controlled, careless handling could induce additional damage. Thus quality control of surface defects, although advocated, [10], is currently of little use, while it requires significant changes in industrial processes and new optical scanning techniques. But this is does not apply to the second determining factor: the compressive surface pre-stress.

The compressive surface pre-stress is often considered to be a constant value. Usually it is not measured during production, as with current technology this is difficult to do in a continuous process. Simply the tempering oven is set to a fast cooling rate for fully tempered glass or a medium cooling rate for heat strengthened glass. The compressive pre-stress has been measured over the surface of fully tempered and heat strengthened glass plates by the authors, [11]. As the data that could be presented in [11] was rather limited, the full results and analysis will be given here and placed into a quality control context.

3 Experimental methodology

Glass panels of dimensions 800 × 400 mm were cut from annealed float glass of 4 mm, 6 mm, 8 mm, 10 mm and 12 mm nominal thickness. These panels were heated following exactly the tempering oven manufacturer guidelines and using the correct settings for the glass thickness being treated.
Experiments were conducted using a scalp 4, laser scanning polarimeter. It was found that to have consistent measurement results the following conditions need to be guaranteed:

- Good optical contact between the scalp device and the glass. This was ensured by using an ample amount of sunflower oil as optical coupling liquid. This was applied using a small spraying bottle.
- Comparable light conditions, preferably not too bright.
- Removal of stickers, labels and other reflective things on the bottom side of the glass.
- It is important to reduce the number of excluded pixels to less than 10% to have a reliable measurement.

A frame was used to ensure the positioning of the scalp device. The setup is shown in figure 1. Measurements with the long axis of the scalp device parallel to the long axis of the glass specimens are labelled as longitudinal (LT). Measurements with the short axis of the scalp device parallel to the long axis of the glass specimens are labelled as transverse (TR). All specimens were placed into the testing setup with the side containing tempering

Figure 1. Test setup

stamps downwards. This on the assumption that thus the same side relative to the position in the quenching oven was consistently used.

The measurements were taken in the centre of a 100 × 100 mm square. If the square was ~~on the~~ outside of the plate, a second measurement was taken as closely as possible to the edge of the plate. In practice this is about 10 mm from the edge. On the long side of the specimen only longitudinal measurements can be taken at the edge, on the short side only transverse measurements.

4 Accuracy of measurement

Critical for any measuring technique is the accuracy of measurement. To determine the reproducibility of measurement, on the first square of each plate the measurement was repeated 5 times without moving the sensor. The results are given in table 2. All sets are comparable in their reproducibility. The average standard deviation is around 3%. Even though, probably through varying quality of optical contact in some measurements causing extra scatter, generally the measurements should have a maximum scatter of ±5%. Measurements in different locations which differ more than this ±5% range should thus imply a physical difference in the pre-stress between the two locations.

Table 2. Reproducibility of Lt compressive surface pre-stress measurement longitudinal square A1

Specimens	Mean (MPa)	Standard deviation (MPa)	Minimum (MPa)	Maximum (MPa)
4 mm HS	45.0	0.94	43.2	45.9
6 mm HS	56.1	1.60	53.6	58.0
8 mm HS	56.3	1.91	54.1	59.7
10 mm HS	47.8	1.08	46.3	49.6
12 mm HS	59.6	1.32	57.4	61.2

5 Compressive pre-stress distribution

The results from the measurement close to the edges are given in an appendix as tables A1, to A4. The surface data is given in tables A5 to A9 and figures A1 to A5. Averages and standard distributions are not given as the data does follow the Gaussian distribution. Maxima and minima are given as they can be determined.

6 Discussion

The weakest spot in a tempered glass specimen is the spot where a large defect and a low residual compressive stress occur together. In practice we can take the minimum strength and add to that the lowest compressive surface pre-stress to find the maximum allowable stress. Edges and top and bottom surfaces need to be looked at separately. Edges are weaker, with strengths as low as 20 MPa, but have on average a higher compressive surface pre-stress. The measured data is not at the edge but 10 mm from the edge. The actual edge compressive pre-stress is likely to be higher. The 40 to 90 MPa surface compressive stress at 10 mm from the edge should translate to a 70 to 120 MPa actual surface compressive stress at the actual edge surfaces. This gives minimum edge strengths of 90 to 140 MPa. In practice in tempered glass tested flat, failures are seldom from the edges but almost always from the surface [12].

Surface strength ranges from 50 to 160 MPa and surface compressive pre-stresses range from 25 to 70 MPa. This lead to strengths of 75 to more than 200 MPa.

In terms of quality control the question now becomes: which part(s) of processes need to be better controlled to improve the reliability of the engineering strength? The results show that high strengths in annealed glass and high compressive pre-stresses due to tempering can be obtained. The primary problem is how to get the minimum values of strength and compressive pre-stress higher. A secondary problem is to decrease the maxima of the compressive pre-stress as higher compressive pre-stresses will result in higher energy release on fracture and thus increased fragmentation. This decreases the residual strength. Although improved edge processing (grinding or water jet cutting) seems a logical choice, the fact that the edges have a significantly higher compressive pre-stress after tempering actually obviates the need for improved edge processing. Higher edge strength would lead to higher failure stress and thus higher fragmentation which is undesirable. Consistent edge quality would be nice, but is only relevant if a consistent compressive pre-stress can be induced by tempering.

In practice thus control of the consistency of the compressive pre-stresses is the most important parameter. Figure 2 shows the average, maximum and minimum compressive pre-stresses at the edges and the surface plotted against thickness. Looking at the compressive surface pre-stresses a range of 30 to 70 MPa is observed. The problem however is that the spread cannot be statistically described with a single function. Figures A1 to A5 show the compressive pre-stress over the surface. All 5 examples are without a clear pattern. Peaks and troughs are effectively random. Additionally, the compressive

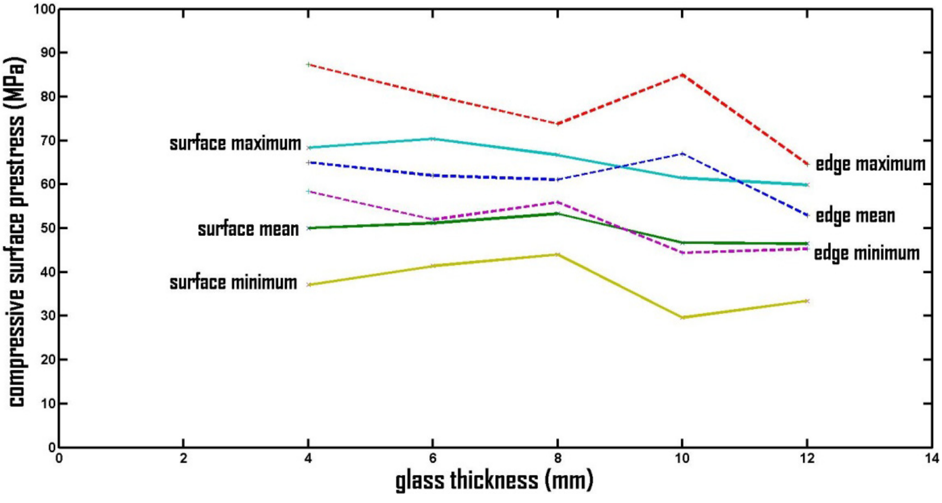

Figure 2. Compressive surface pre-stresses in relation to glass thickness

pre-stresses are direction dependent. On some locations the Lt and Tr stresses are virtually equal, on other locations (e.g. locations C7 in table A9 and B6 in table A6) there is almost a factor 2 between the Lt and Tr compressive pre-stresses. Of course the compressive pre-stress at right angles to the crack determines the reduction in stress intensity. Analysing a tempered plate looking only at the stresses in one direction is thus dangerous as it neglects the potential lower compressive pre-stresses in other directions.

The next problem is: can the spread in compressive pre-stress be universally described by a single statistical distribution model. Figure 3 shows a normal distribution plot and figure 4 a log normal probability plot of the surface compressive pre-stresses only, without the higher values near edges. The 4 mm data shows a reasonable fit for the normal distribution while the 8 mm data shows a reasonable fit for the log normal distribution. The other data sets however do not fit onto these distributions. Other distribution patterns have been tried, but no single statistical distribution universally fits all data. In practice, this implies that the deviations not only result from the expected statistical variations in the processes, but that deterministic variations in conducting the processes are superimposed on the statistical variations, thus generating an apparently random pattern.

This is not surprising. The process of tempering is well described by Karvinen and Mikkonen in [13]. Essentially the value of the compressive pre-stress is determined by the cooling rate. Inconstant compressive pre-stresses thus imply that the cooling rates were inconstant. Considering that the cooling takes place by blowing air from nozzles over the hot glass surface and edges, cooling conditions cannot be equal everywhere. Directly

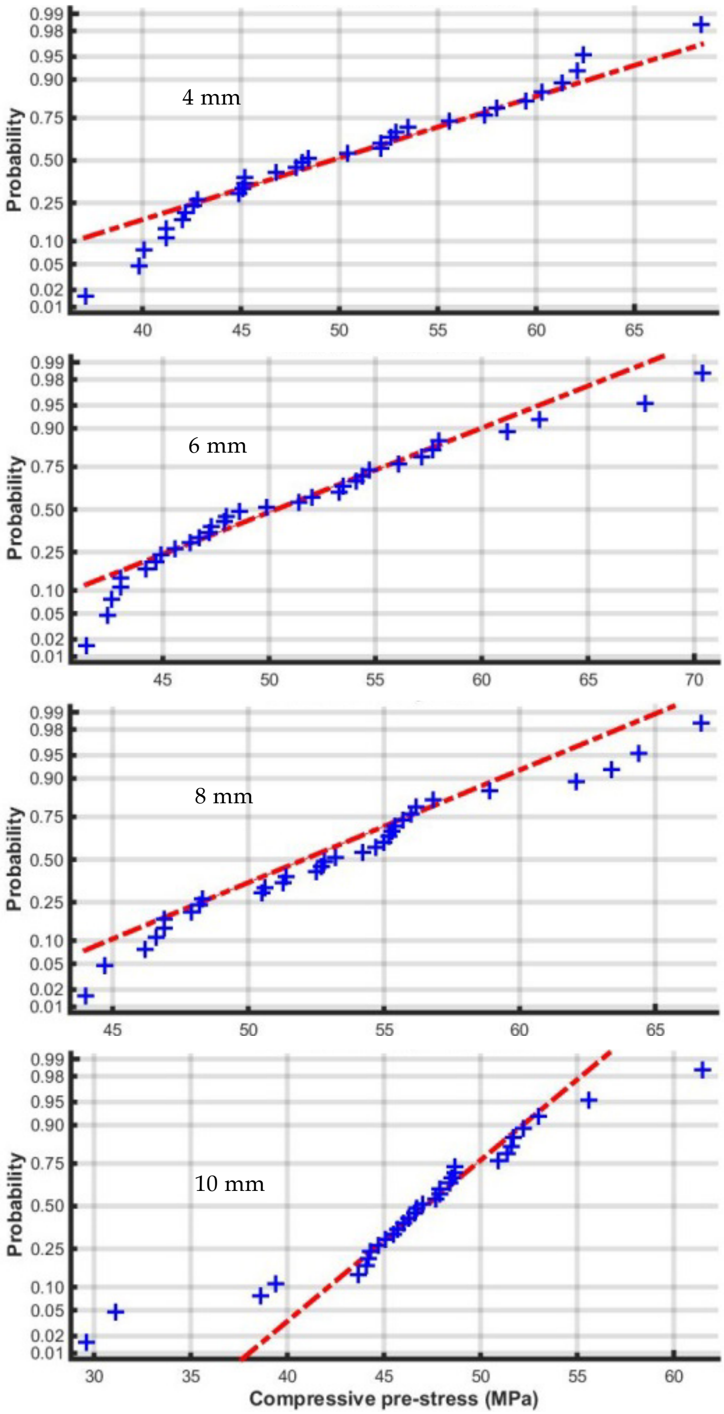

Figure 3. Normal probability plots Lt compressive pre-stresses 4 to 10 mm specimens

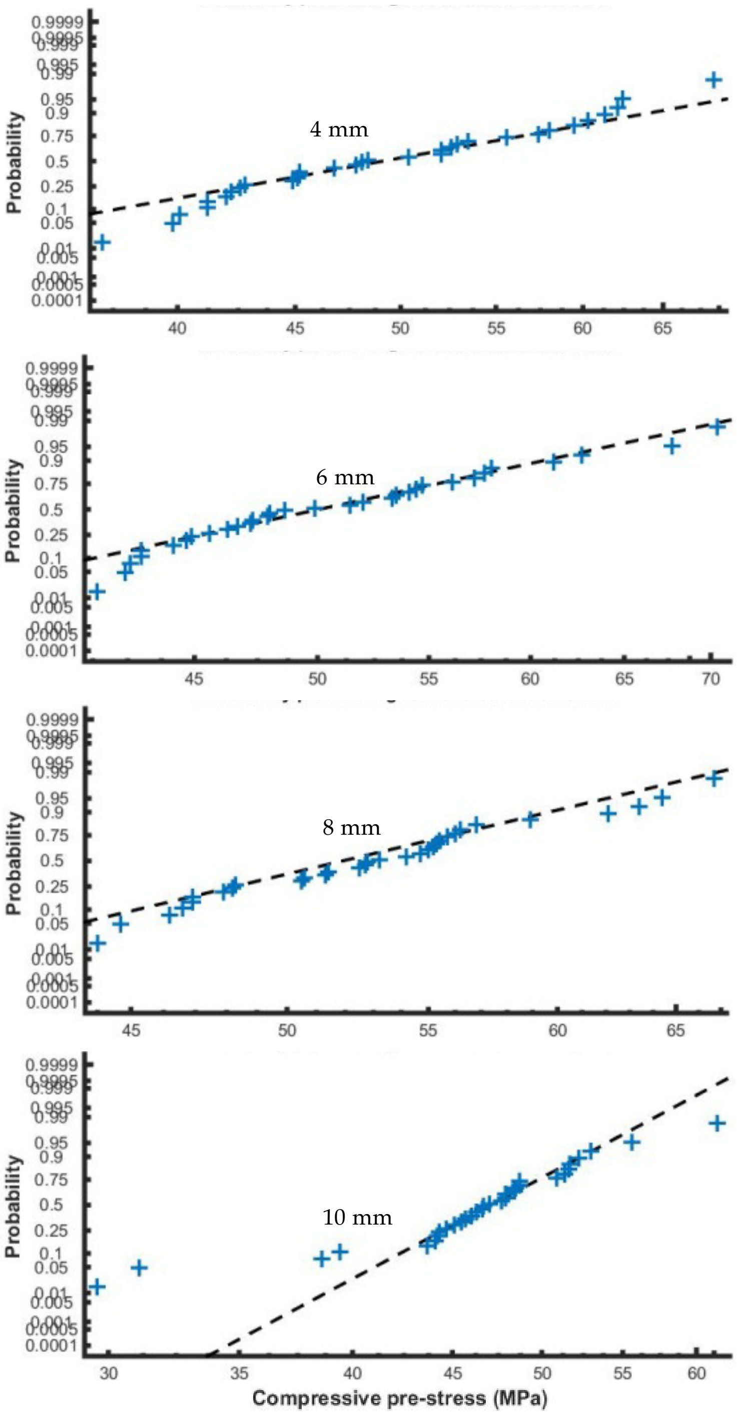

Figure 4. Lognormal probability plots Lt compressive pre-stresses 4 to 10 mm specimens

under the nozzle the air volume will differ from a position in between nozzles. In addition, the size of the plates and the distance of the plates will affect the airflow and thus the cooling rate. Additionally, the positioning over the roller bars at the cooling start will probably highly influence the eventual pre-stressing. This results in deterministic variations which however should be avoidable by improved machine and process design. Thus quality control requires a consistent starting temperature and a consistent cooling rate over the whole surface and over the length of the edges. In practice this should aim at a minimum compressive surface pre-stress of 40 MPa with a maximum of 60 MPa. This would result in a minimum surface strength of 80 MPa and a maximum of 120 MPa. This is still significantly more spread than exists for steel or concrete, but a significant improvement over the current situation.

7 Conclusions

From the results the authors conclude that:

- The variations in compressive surface pre-stresses which are induced by tempering are not a solely statistical quantity but are also the result of deterministic effects during the heating and cooling in the tempering cycle.
- Improvements in the design of tempering machines and processes are required to provide adequate quality control of the strength of heat strengthened glass.
- Improvements in edge quality are at best secondary because the tempering process induces higher compressive pre-stresses at the edges which effectively compensates for the lower quality of the edges.
- A homogeneous edge and surface quality in terms of defects will contribute to predictability of the strength of tempered glass. However the size, geometry and nature of the defects involved makes quality control with current technologies impossible as optical inspection cannot find these defects.

References

[1] Guidance for European Structural Design of Glass Components, 2014, Published by European community and available on: http://publications.jrc.ec.europa.eu/repository/handle/JRC86637 retrieval date 11 of march 2016

[2] F.A. Veer, P.C. Louter, F.P. Bos, The strength of annealed, heat-strengthened and fully tempered float glass, *Fatigue and fracture of engineering materials and structures*, Vol 32, 2009

[3] M. Badalassi, L.Biolzi, G. Royer-Carfagni , W. Salvatore, Calibration of partial safety factors for the structural design of glass, Paper on: http://www.ativ-online.it/IRSAGauthorsGianni%20Royer.htm, retrieval date ~~retrieval date~~ 11 march 2016

[4] Xiangqian Peng, Youping Chen, Wenyong Yu, Zude Zhou, Guodong Sun, An online defects inspection method for float glass fabrication based on machine vision, *The International Journal of Advanced Manufacturing Technology,* December 2008, Volume 39, Issue 11-12, pp 1180-1189

[5] F.P. Bos, *Safety concepts in structural glass engineering*, PhD thesis, Delft University of technology, 2009

[6] M. Janssen, J. Zuidema, R.J.H. Wanhill, *Fracture Mechanics*, Delft Academic Press, 2002

[7] M. Overend ,C. Louter, The effectiveness of resin-based repairs on the inert strength recovery of glass, *Construction and Building Materials* 85 (2015), p 165–174

[8] F.A.Veer, The strength of glass, a non-transparent value, *HERON*, Vol 52, 2007

[9] S.M. Morse, H. Scott Norville, Experimental studies of weather tempered glass plates, *Proceeding GPD 2015*, Tampere, Finland

[10] Y.M. Rodichev, N.Tregubov, The Challenge of Quality and Strength of the Hardened Architectural Glass, *Proceeding GPD 2009*, Tampere, Finland

[11] F.A.Veer, Y.M. Rodichev, Variations in pre-stress in annealed, heat strengthened and fully tempered glass, *Proceeding GPD 2015*, Tampere, Finland

[12] F.A.Veer, Y.M. Rodichev, The strength of glass, size effects, *Proceeding GPD 2013*, Tampere, Finland

[13] R. Karvinen, A. Mikkonen, Effect of heat transfer on glass quality in tempering, *Proceedings glass processing days 2015*, Tampere, Finland 2015

Appendix

Table A1. Left Edge LT compressive surface pre-stresses long side (MPa)

Position	4 mm	6 mm	8 mm	10 mm	12 mm
1	59.2	64.3	73.8	69.7	63.2
2	68.3	57.4	64.3	66.3	64.6
3	65.4	59.1	62.5	62.8	57.2
4	59.6	64.7	58.9	65.4	54.0
5	67.4	60.1	57.3	68.5	53.1
6	61.3	58.2	57.7	77.0	50.1
7	62.8	57.3	55.9	72.3	49.6
8	58.4	52.0	58.6	70.9	51.3
Maximum	68.3	64.7	73.8	77.0	64.6
Minimum	58.4	52.0	55.9	62.8	51.3

Table A2. Right Edge LT compressive surface pre-stresses long side (MPa)

Position	4 mm	6 mm	8 mm	10 mm	12 mm
1	85.5	58.4	71.2	55.9	63.2
2	70.6	64.4	69.6	85.0	65.4
3	61.2	58.3	60.2	75.4	61.2
4	58.4	53.2	58.3	69.2	45.4
5	87.3	80.3	62.3	72.6	48.6
6	63.2	61.1	63.4	67.4	51.2
7	66.9	62.1	65.6	44.4	45.3
8	72.6	70.6	60.2	59.8	51.2
Maximum	87.3	80.3	71.2	85.0	65.4
Minimum	58.4	53.2	58.3	44.4	45.3

Table A3. Top edge Tr compressive surface pre-stresses short side (MPa)

Position	4 mm	6 mm	8 mm	10 mm	12 mm
A	79.5	61.2	64.3	64.4	51.6
B	69.8	60.5	58.2	50.7	53.4
C	68.6	80.1	56.5	48.9	48.9
D	61.2	67.5	60.5	58.4	59.3
Maximum	79.5	80.1	64.3	64.4	59.3
Minimum	61.2	60.5	56.5	48.9	48.9

Table A4. Bottom edge Tr compressive surface pre-stresses short side (MPa)

Position	4 mm	6 mm	8 mm	10 mm	12 mm
A	59.9	57.4	54.2	59.6	47.2
B	66.9	63.8	71.2	69.2	46.4
C	59.6	57.1	55.4	89.2	52.1
D	64.3	59.4	68.6	71.4	56.3
Maximum	66.9	63.8	71.2	89.2	56.3
Minimum	59.6	57.1	54.2	59.6	46.4

Table A5. Surface compressive pre-stress 4 mm HS specimen

position	A		B		C		D	
	Lt	Tr	Lt	Tr	Lt	Tr	Lt	Tr
1	45.2	61.2	42.6	56.4	52.1	64.4	55.6	53.2
2	44.9	46.1	57.4	61.4	42.2	42.1	46.8	47.0
3	40.1	42.6	52.6	53.4	61.3	36.5	47.8	56.6
4	52.1	56.4	45.1	46.5	48.4	40.1	42.0	38.9
5	37.1	43.0	62.4	55.8	58.0	43.2	50.4	44.2
6	39.8	45.1	62.1	43.9	59.5	28.4	41.2	46.3
7	41.2	35.9	53.5	44.2	52.9	39.4	45.2	61.2
8	42.8	41.2	68.4	52.9	60.3	46.3	48.1	52.9
Lt	max	68.4	min	37.1				
Tr	max	64.4	min	28.4				

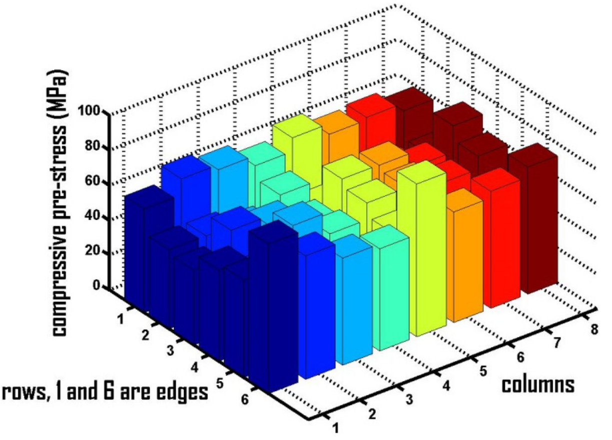

Figure A1. LT surface compressive pre-stress 4 mm HS specimen

Table A6. Surface compressive pre-stress 6 mm HS specimen (MPa)

Position	A		B		C		D	
	Lt	Tr	Lt	Tr	Lt	Tr	Lt	Tr
1	58.0	42.2	53.3	42.5	49.9	37.1	57.2	43.9
2	45.6	48.5	41.4	50.3	54.7	36.5	51.4	56.6
3	47.3	52.8	48.0	59.3	44.9	45.4	48.6	39.0
4	54.1	38.7	67.7	42.9	54.4	45.4	42.4	75.3
5	42.6	46.0	46.7	43.6	43.0	31.0	44.7	40.9
6	52.0	52.6	62.7	38.0	53.5	46.1	56.1	45.2
7	44.2	53.4	47.9	43.5	47.2	43.4	70.4	49.3
8	46.3	45.4	57.7	50.3	61.2	46.8	43.0	42.2
Lt	max	70.4	min	41.4				
Tr	max	75.3	min	31.0				

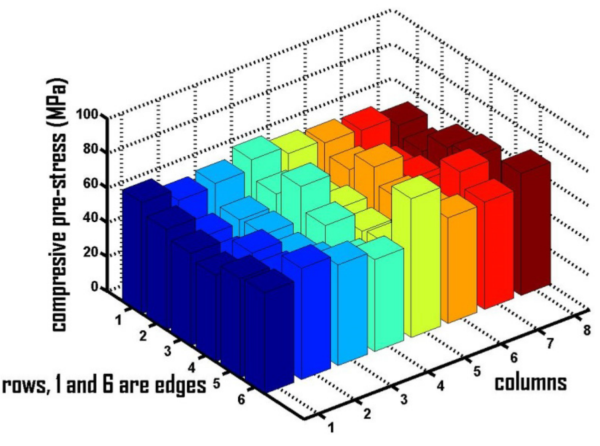

Figure A2. LT surface compressive pre-stress 6 mm HS specimen

Table A7. Surface compressive pre-stress 8 mm HS specimen (MPa)

position	A		B		C		D	
	Lt	Tr	Lt	Tr	Lt	Tr	Lt	Tr
1	55.0	50.2	54.2	51.9	44.0	46.1	66.7	53.8
2	55.3	43.1	55.4	44.9	54.7	61.2	63.4	48.8
3	52.7	53.5	46.2	52.0	50.6	50.1	46.6	54.5
4	55.2	51.4	56.2	56.9	47.9	54.3	46.9	52.1
5	46.9	62.2	55.7	49.0	52.5	43.9	56.8	48.6
6	52.8	53.1	64.4	48.6	56.0	49.8	58.9	49.2
7	44.7	52.1	50.5	49.2	51.4	58.4	62.1	46.3
8	48.3	40.8	53.2	62.4	48.2	48.9	51.3	62.8
Lt	max	66.7	min	44.0				
Tr	max	62.8	min	40.8				

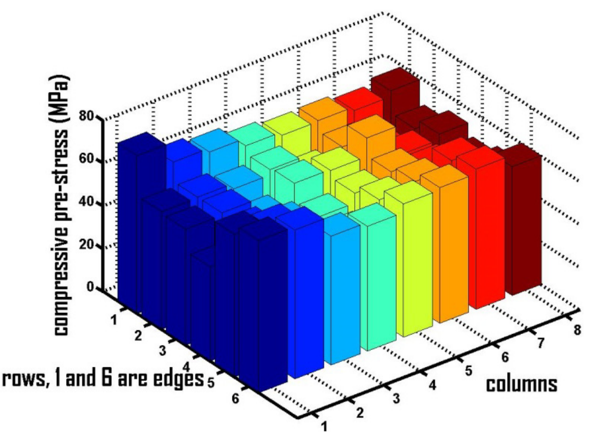

Figure A3. LT surface compressive pre-stress 8 mm HS specimen

Table A8. Surface compressive pre-stress 10 mm HS specimen(MPa)

Position	A		B		C		D	
	Lt	Tr	Lt	Tr	Lt	Tr	Lt	Tr
1	47.9	39.6	44.1	43.7	29.6	44.9	31.1	46.1
2	48.5	43.4	47.0	48.0	55.6	38.7	61.5	56.0
3	52.2	47.2	46.3	48.3	51.6	39.9	44.2	57.0
4	48.7	52.7	46.7	45.6	48.7	53.1	46.6	42.9
5	46.0	37.4	47.9	45.6	48.7	53.1	46.6	42.9
6	48.4	57.6	44.3	43.9	45.5	37.9	53.0	44.0
7	51.4	61.3	51.7	48.9	45.7	52.5	43.7	52.6
8	45.1	50.6	44.7	57.4	47.7	46.0	39.4	46.3
Lt	max	61.5	min	31.1				
Tr	max	61.3	min	37.4				

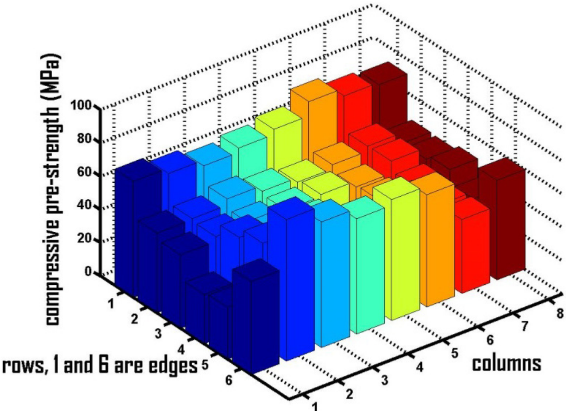

Figure A4. LT surface compressive pre-stress 10 mm HS specimen

Table A9. Surface compressive pre-stress 12 mm HS specimen (MPa)

Position	A		B		C		D	
	Lt	Tr	Lt	Tr	Lt	Tr	Lt	Tr
1	59.9	37.6	48.5	50.7	43.0	39.9	56.1	55.5
2	51.8	39.2	53.6	47.0	47.9	47.5	50.5	43.3
3	50.0	45.0	52.1	36.3	39.9	40.6	51.5	44.7
4	43.3	48.3	46.6	52.4	41.9	42.6	48.5	36.4
5	44.6	57.0	44.7	40.6	44.9	46.0	39.8	44.1
6	44.5	40.2	51.7	40.4	51.2	41.5	47.8	58.1
7	33.4	42.3	43.5	35.8	33.8	51.5	42.3	39.7
8	45.9	35.7	41.5	43.8	51.0	51.6	42.9	63.6
Lt	max	59.9	min	33.4				
Tr	max	63.6	min	35.8				

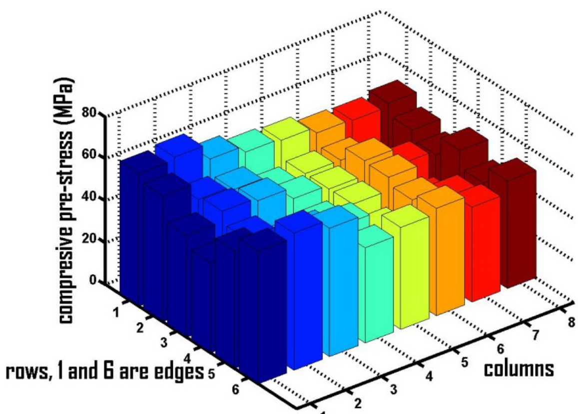

Figure A5. LT surface compressive pre-stress 10 mm HS specimen