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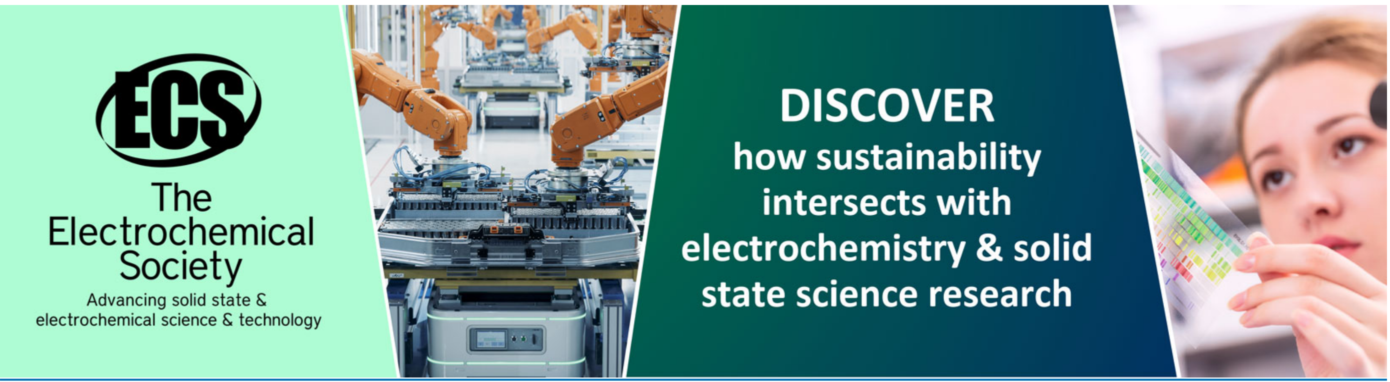

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Influence of pre-loading on the flexural behaviour of annealed glass

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Abstract. Transparency, a highly sought aspect in architectural applications, has led to rising demand for glass in buildings and other structures. The changeover of the role of architectural glass makes it inevitable to characterize the mechanical properties of glass as individually as has been done for all other conventional materials employed in structural applications. Thus the awareness of glass strength is vital for the design of transparent structures made of structural glass. The present work reports displacement-controlled four-point bending tests performed on a set of annealed glass specimens to study the effect of pre-loading value and its duration on the flexural behaviour. Analysis of variance is carried out in Minitab 19 to study the effect of pre-loading and thickness of glass on the failure stress ratio. Analysis of variance results show that pre-load is the most significant factor for the failure stress ratio.

1. Introduction

Recent technological developments and architectural trends have generated unparalleled opportunities and major breakthrough in the use of glass in buildings. Glass has become an inevitable part of green buildings owing to its contribution to aesthetics, day lighting, transparency, easy maintenance and sustainability. The most common glass production processes, processing methods and glass products are reported by Haldimann et al. [1]. Glass structures have the potential to blend and become transparent, almost dematerialized when the connections are kept to a minimum. Enormous developments in the glass industry have led to the increased structural use of glass in demanding applications (see Figure1) [2-5].

(a) (b) (c)

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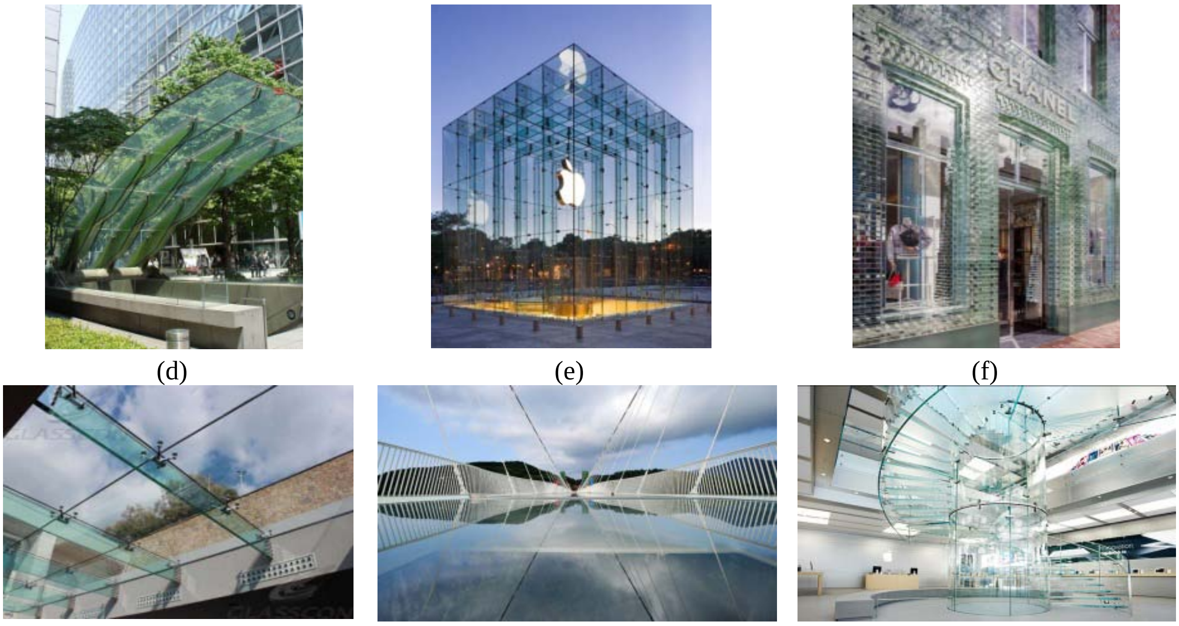


(d) (e) (f)

(g) (h) (i)

Figure 1. (a) Headquarter in Ipswich, England, (b) Local Authority Office in Saint-Germain-en-Laye, (c) Foot bridge in Rotterdam, Netherlands, (d) Glass canopy at Yurakucho underground railway station in Tokyo, Japan, (e) All glass cube at Apple store, New York, (f) Crystal house in Amsterdam, (g) Glass roof above interior courtyard for the International Chamber of Commerce in Munich, Germany, (h) Pedestrian glass bridge in China, (i) Glass stair in Apple store, New York [2-5]

A significant amount of research work [1, 5-34] is being carried out to enhance the perception of the load-bearing capability of glass components under the actions (flexure, compression, impact, blast, thermal exposure, fatigue etc.) to which these elements are subjected during their service life. Structural design can be considered to be reliable only if it can accurately assess the material failure strength. The most utilized techniques to gauge the mechanical strength of glass at the macroscopic level are the Four-Point Bending test [6, 7, 12, 18, 20, 24-26, 31-33, 35] and the Coaxial Double Ring (CDR) test [8, 14, 16, 19-21, 32]. Usually, these tests are performed either displacement-controlled[6-8, 12, 18, 20, 24, 29, 31-33], or stress-controlled [7, 22, 25, 26, 31]. The rate of loading adopted for the majority of stress-controlled tests is 2 MPa/s [35] whereas it mostly varies from 0.1 to 10 mm/minute for displacement-controlled tests. The empirical values obtained for the failure strength will be lower than the theoretical values owing to the presence of hidden damages. Such damages can be managed and minimized using theory and experimental data in combination with advanced glass processing technologies and strength control methods [7, 18, 22, 29].This necessitates an experimental assessment of the actual failure strength of glass. Most of the researchers adopted the bending test for this purpose as it meticulously matches the experimentation performed on other materials, is relatively economical, is simple to execute, and stresses the edges of the glass. The two most prevalent techniques for transforming annealed glass into a safe structural material are tempering (lowers the probability of failure) and lamination (lessens the consequence of failure) [6, 12, 18, 24, 25, 33, 36]. Minute flaws having different geometries and orientations will be present on the surface of glass plates as a result of manufacturing process. In-service exposure significantly reduces the strength of glass. Local stress concentrations arise on a loaded glass plate as a result of the interaction between the surface flaws and surface tensile stresses. In the presence of water vapour, the exposure of surface flaws to tensile stresses results in glass strength reduction and this phenomenon is referred to as static corrosion or static fatigue. When the local stress allied with one of the flaws becomes large enough to initiate fracture, the failure of glass plate occurs. The influence of pre-loading on the failure strength of glass specimens is not reported in these literatures. Also only limited research on structural glass is carried out in our country. Thus it entails a detailed research in this area.

In the present work, displacement-controlled four-point bending tests are conducted to investigate the response of annealed glass specimens of varying thickness. The stiffness and maximum tensile stress of the various glass specimens are studied. A separate set of annealed glass specimens are pre-loaded for duration of one day and then tested to failure under four-point bending. An Analysis of Variance (ANOVA) is carried out in Minitab 19 to study the effect of pre-load and thickness of glass on the failure stress ratio.

2. Experimental study

The test specimens and procedure are described in the following sections.

2.1. Specimens

Total of 30 annealed glass samples (see Table 1), obtained from a single manufacturer, new, in the as-received condition, is tested to scrutinize the influence of pre-loading on the flexural behaviour of the glass panes.

Table 1. Details of the glass specimens

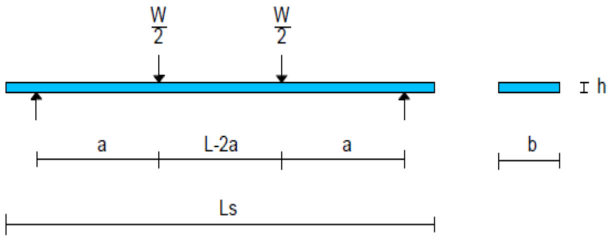
Type of glass	Length (mm)	Width (mm)	Thickness (mm)	Number of samples
Annealed Glass	700	100	8	10
Annealed Glass	700	100	10	10
Annealed Glass	700	100	12	10

2.2. Procedure

Deflection-controlled four-point bending tests are carried out on the different glass specimens in MATEST Loading Frame. Each specimen is placed in the lying position, on the specially fabricated four-point bending test jig, and loaded at the rate of 0.1 mm/minute (see Figure 2). Load span and support span are kept as 200 mm and 600 mm respectively. The compression side of the test samples is wrapped with a transparent adhesive tape as a safety measure to reduce personal injuries. A lower stiffness value for the tape ensures fragmentation and allows free expansion of glass. Rubber pads are kept between the glass specimens and the rollers to avoid uneven load distribution and to reduce friction between them. Load–deflection behaviour as well as the crack pattern of the specimens are noted. The average temperature and humidity during the bending tests are 31^{o}C and 75% respectively. From the load-deflection data, the values of stiffness and maximum tensile stress are calculated using the fundamental equations.

Annealed glass specimens (8 mm, 10 mm and 12 mm thick) are used to study the effect of pre-loading value and its duration on the flexural behaviour. In the present investigation, pre-loading duration of one day and pre-loading values corresponding to 0.50 times the failure strength of the annealed glass specimens tested without pre-loading are adopted for half of the samples. The specimens are pre-loaded in the same four-point test jig. Four-point bending tests are performed on all the specimens after pre-loading to examine the variations in the mechanical properties.

(a)



Where, W is the load, a is the distance between support and loading rollers, L is the support span, b is the width of the specimen, h is the thickness of the specimen and L_s is the length of the specimen

(b)

Figure 2. (a) Test setup (b) Schematic diagram

3. Results and discussion

The test results are tabulated in Table 2.The scatter diagram of the failure stress values obtained for the samples used to study the effect of pre-loading is shown in Figure 3.

Table 2. Four-point bending results of pre-loaded annealed glass specimens

Particulars	8 mm thick glass panes				10 mm thick glass panes				12 mm thick glass panes			
	Without pre-load		With pre-load		Without pre-load		With pre-load		Without pre-load		With pre-load	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Failure load (kN)	0.170	0.039	0.025	0.005	0.196	0.067	0.075	0.030	0.526	0.149	0.350	0.118
Maximum deflection (mm)	2.26	0.46	0.38	0.05	1.46	0.46	0.62	0.22	2.28	0.62	1.53	0.47
Stiffness (N/mm)	70.43	3.86	63.33	4.03	133.14	8.00	117.32	5.50	230.23	4.41	226.92	7.03
Failure stress (MPa)	15.91	3.64	2.31	0.44	11.73	3.99	4.51	1.82	21.91	6.19	14.58	4.92

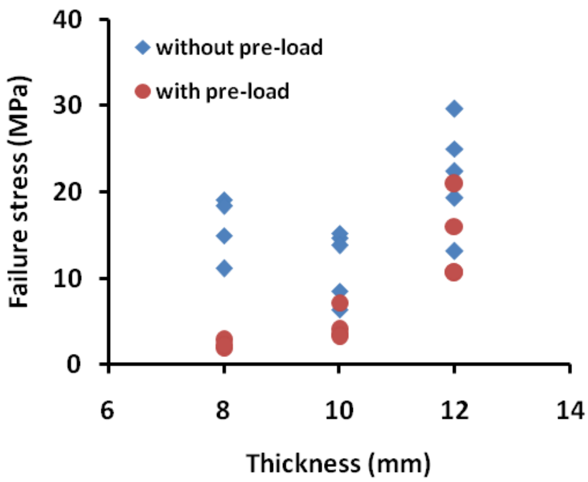


Figure 3. Scatter plot of the failure stress values of annealed glass specimens with and without pre-load

3.1. Fracture pattern
All the test samples showed expected brittle failure but exhibited linear elastic behaviour until failure. All the glass panes smashed as and when the respective failure load is reached. For all the annealed glass specimens, fracture originated from the edge, propagated for some distance and further crack branching occurred with two or three branches. The fracture pattern of the test specimens is shown in Figure 4.

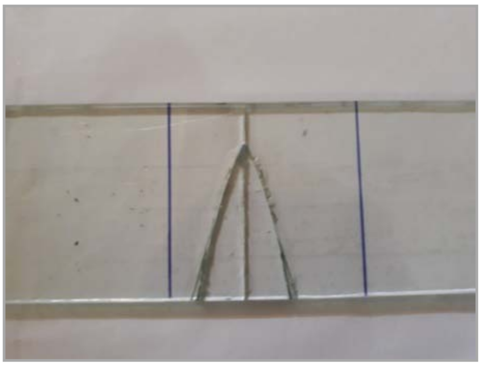


Figure 4. The fracture pattern of the annealed glass samples

3.2. Effect of pre-loading
A majority of the pre-loaded specimens attained lower values for failure load, maximum displacement, stiffness, and failure stress, compared to that of samples tested without pre-loading. After pre-loading, both the maximum load and tensile stress values showed a similar reduction of 34%, 62% and 85% for 12 mm, 10 mm and 8 mm thick samples respectively. The annealed glass panes displayed an analogous decline of maximum deflection values (33%, 58% and 83% for 12 mm, 10 mm and 8 mm thick panes correspondingly). The test specimens exhibited only a slight drop in the stiffness values (2%, 12% and 10% for 12 mm, 10 mm and 8 mm thick panes accordingly). Thus the deterioration in the parameters discussed above displayed a negative relationship with the thickness of glass pane and may be due to the variations in the existent flaw density of samples during testing. The impact of pre-loading on the flexural behaviour of annealed glass specimens is illustrated in Table 3. All the ratios shown in Table 3 are obtained by dividing each parameter value got with pre-load by corresponding value acquired without pre-load.

Table 3. Effect of pre-loading on the flexural behaviour of annealed glass samples

Sl. No.	Particulars	Thickness (mm)		
		8	10	12
1	Maximum load ratio	0.15	0.38	0.66
2	Maximum deflection ratio	0.17	0.42	0.67
3	Stiffness ratio	0.90	0.88	0.98
4	Maximum tensile stress ratio	0.15	0.38	0.66

The parameters excluding stiffness show a fairly strong positive relationship with the thickness of glass tested with pre-load.

3.2.1. General linear model for failure stress ratio in ANOVA. The factors and their levels considered for the general linear model of failure stress ratio (see Table 4), and ANOVA results (see Table 5 and Figure 5) are presented in this section.

Table 4. Factors considered for the general linear model of failure stress ratio in ANOVA

Factor	Levels	Values
Thickness	3	8 mm, 10 mm, 12 mm
Pre-load type	2	0(without pre-load), 1(with pre-load)

Table 5. Analysis of variance for failure stress ratio

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Thickness	2	0.2064	0.10320	1.51	0.243
Pre-load type	1	2.0779	2.07792	30.48	0.000
Error	21	1.4315	0.06817		
Lack-of-Fit	2	0.2661	0.13304	2.17	0.142
Pure Error	19	1.1654	0.06134		
Total	24	3.7010			
*S = 0.261089	R-sq = 61.32%		R-sq (adj) = 55.80%	R-sq (pred) = 45.89%	

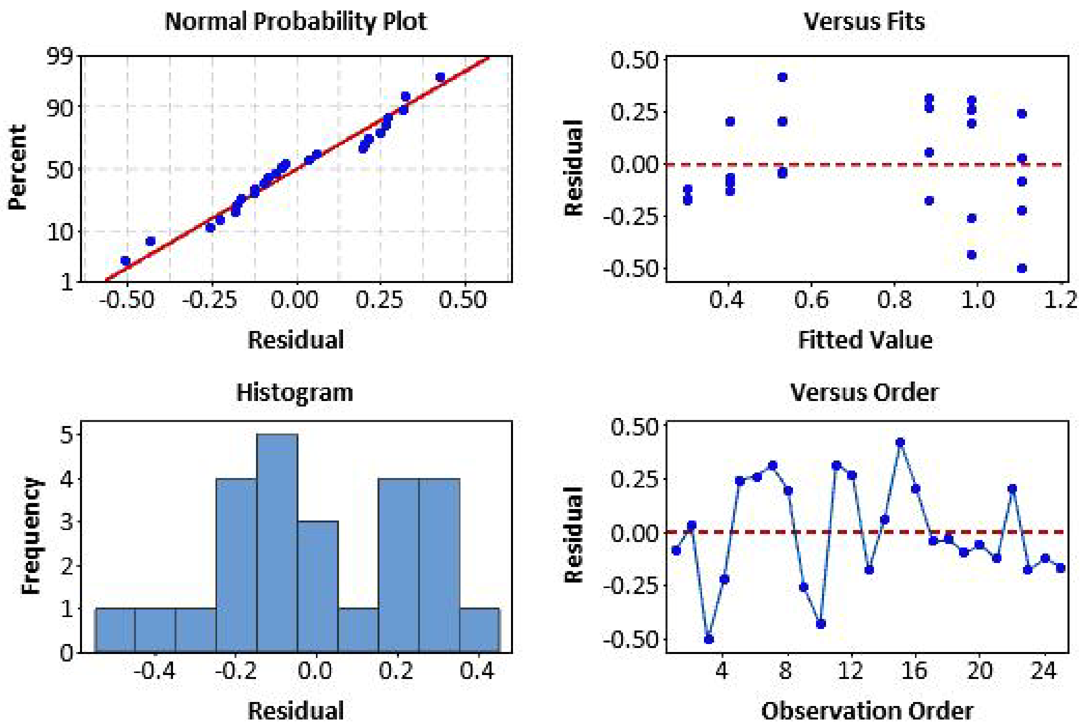


Figure 5. Residual plots for failure stress ratio

The F-values and P-values of the thirty samples tested (see Table 5) clearly indicate that the failure stress ratio is strongly dependent on the ‘type of pre-load’ (see Table 4) followed by the ‘thickness of glass’. Even though the normal probability plot qualifies the fat pencil test, observation 3 has unusual observation with a failure stress ratio of 0.601, Fit of 1.110, a residue of -0.509 and standard residue of -2.11.

The appearance of the histogram shows that the model meets the model assumptions and the residuals are normally distributed. Also the residuals are independent from one another as they fall randomly around the centre line on the plot.

The regression equation obtained by ANOVA (see Eq. (1)) satisfactorily predicts the mean failure stress ratio value (FSR) corresponding to each thickness of the pre-loaded sample (0.145, 0.385, and 0.666 for 8 mm, 10 mm and 12 mm thick samples respectively).

$$FSR = 0.3986 - 0.2533 \text{ Thick\_8} - 0.0137 \text{ Thick\_10} + 0.2670 \text{ Thick\_12} \qquad (1)$$

4. Conclusions

The following conclusions are made out of the present experimental and analytical study conducted on annealed glass specimens of different thickness. All the glass panes smashed as and when the respective failure load is reached showing expected brittle failure but exhibited linear elastic behaviour until failure. Cracks are more confined in lower strength specimen and could be ascribed to a local defect. Wide scatter in test data for annealed samples may be attributed to the presence of flaws.

Pre-loading resulted in reduction in stiffness value (in the range of 2-12%) for all the considered cases. The findings support the dependence of failure stress ratio on the application of pre-load and the thickness of glass.

The general linear model developed in ANOVA highlights that the pre-load type is the most significant factor for the failure stress ratio and one-way ANOVA results indicate the influence of thickness of the glass on the failure stress ratio. The regression equation obtained by ANOVA is valid for the specific type of glass and testing conditions considered for the present study; the generalization of such relation requires further intense investigation.

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