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Effect of span length of flexural testing on glass properties

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3-point bend test and fractography analysis were carried out to study the effect of span length (40, 60, 80, 100, 120, 140 mm) on mechanical properties such as flexural strength, stiffness, strain energy and flexural modulus. The flexural strength in terms of the span length-deflection ratio was plotted to determine the transition point from shear to flexural fracture. The correlation between flexural strength, mirror strength as a function of the span length was investigated as well. The results showed the span length had affected the flexural strength as well as the mirror strength. We also reported that the mirror radius was inversely proportional to the flexural strength and the mirror constant was fluctuated in the range of 45.1 MPa · (mm)$^{1/2}$ to 67.4 MPa · (mm)$^{1/2}$.

Key words: 3-point Bend Test, Flexural Strength, Mirror Radius, Mirror Constant, Span Length.

Introduction

The study of glass strength has been a fascinating area and a convenient way to test the strength is to perform centrally loaded three-point beam bending. The measured strength in this testing is called the modulus of rupture (MOR) [1, 2, 4-6]. In a three-point loading scheme, a rectangular glass is placed on two supporting spans and loaded with a force F in the middle. Thus maximum tension is on the convex surface. In the MOR test, the most serious problem is that flexural formula is valid only for linear beam theory, for example the center deflection should not exceed the beam height [1]. This issue is probably more critical when the beam thickness is getting thinner and thinner due to large deflection.

Recently, because of this issue, advanced testing methods such as a vertical MOR and 2-point bend test are introduced to do right evaluation of strength in thin glasses [2, 3]. However, the 2-point bend test is only applicable for ultrathin glasses less than 100 μm thick and the vertical bend test is rarely considered as a test method for thin or ultrathin glasses due to the buckling issue.

Therefore, in this study, we reconsidered the 3-point bend test to understand how deflection in terms of the span length in thin glass affects the mechanical properties such as flexural strength, stiffness, deflection, strain energy and flexural modulus. Fractography analysis was used to determine the origin of failure and the stress for fracture. Correlation among the span length, the flexural strength and the mirror strength was discussed in detail.

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Experimental Procedure

The glass used in this study was a commercial alkali-free glass (0.5 mm EXG, manufactured by Corning Precision Materials Co., Ltd, South Korea) especially developed for LCD display. The glass was cut into rectangular bar-shaped specimens (cross section: 10 mm × 0.5 mm)

3-point bend test was carried out using an Instron (5566, Canton, MA) with a various span length (40, 60, 80, 100, 120, 140 mm). In measurement, the break side of specimen faced onto the supporting span to exclude the disturbance variable factors such as chips, flaws, and crack etc. To keep the pieces of the specimen together after failure, adhesive tape was used at least on the non-tensile surfaces. The cross-head speed was 10 mm/min and the load-displacement curves were recorded with PC-computer software. 25 measurements were made per the span length. Flexural strength (σ) and flexural modulus (E) were calculated from the following equations;[7]

$$\sigma = 3FL/(2bh^2) \tag{1}$$
$$E = SL^3/(4bh^3) \tag{2}$$

Where F and L are the applied load and the span length; b, h, and S are the width of test specimens, the thickness of test specimen, and the stiffness respectively. Here, the stiffness was obtained in the straight-line portion of strain-stress curve. The experimentally obtained depth of deflection in terms of the span length was compared with the values calculated theoretically. The theoretical maximum deflection (δ) was estimated by given following equation;[8]

$$\delta = FL^3/(4Ebh^3) \tag{3}$$

where E is the Young's modulus (73.5 GPa reported by glass manufacturer). To estimate the ability of the glass to absorb mechanical energy until fracture, the strain energy (MPa) was calculated as the integral of the area under the stress-strain curve.

In order to figure out the correlation between the bending strength and the mirror strength per the span length, the mirror radius was measured using an optical microscope (MM6CPC310-2; Olympus, Tokyo, Japan) and then the mirror constant was obtained from the slope of the strength-mirror radius curve. To calculate the mirror strength ($\sigma_{mirror\ strength}$), the mirror constant, A, was put into the equation written as;

$$\sigma_{mirror\ strength} = A/(r^{1/2}) \quad (4)$$

where A and r are the mirror constant and the mirror radius respectively.

Results and Discussion

Mechanical properties such as flexural strength, stiffness, strain energy and flexural modulus were measured and calculated to understand the effect of the span length on 3-point bend strength and the results were summarized in Table 1. With increasing the supporting span length from 40 mm to 140 mm, the mean flexural strength with standard deviation decreased and the depth of deflection linearly increased. Literature said that the decrease of bending strength with increasing the supporting span length is due to the deformation which can reduce the bending strength [1, 9]. Here we calculated the theoretical maximum deflection (δ) using with equation (3) and compared the results with the values measured experimentally. It was observed that the experimentally measured values were slightly low when it was compared to the value calculated theoretically. However both of them have a linear relationship as a function of the supporting span.

On the other hand, the stiffness data obtained from the slope of stress-strain curve showed a non-linear increase with decreasing the span length. The strain energy to estimate the ability of the glass to absorb mechanical energy until fracture was calculated from the integral of the area under the stress-strain curve. It was observed that the maximum value was obtained with specimen of 80 mm span length.

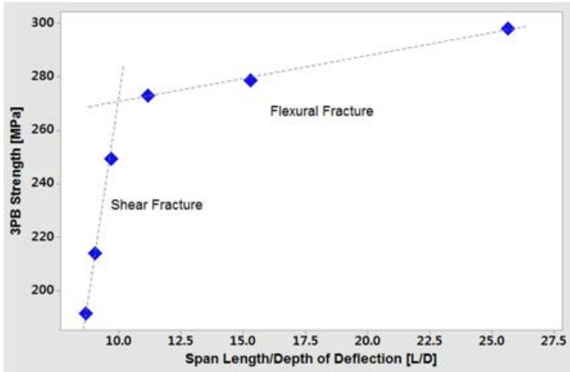

Fig. 1. Bending strength according to the span length/depth of deflection ratio.

Flexural modulus was calculated by using the equation (2). The data calculated in this experiment were a little bit high compared to the Young's Modulus (73.6 GPa) reported by glass maker and the values increased with decreasing the span length. We are assuming that the difference in modulus could be caused by measuring method as well as sample conditions (some deviation in glass thickness and width of specimen). Even though that, it is worth to note that the flexural modulus increased with decreasing the span length, and this result proved that the glass properties based on the bending strength have a dependence of its measuring condition.

In Figure 1, the values of bending strength are described in dependence of the span/depth ratio (supporting span length / depth of deflection). The transition from shear to flexural fracture was observed at around 11. It means that the supporting span length should be below 80 mm to make 0.55 t thin glass flexural fracture. In addition, it should be noted that the critical point from shear fracture to flexural fracture which we observed in this study is good agreement with the values reported by Schneeweiβ group [9]. For the flexural fracture, thus the bending test should be carried out with the span length from 80 mm to 40 mm

Table 1. Measured and calculated glass properties according to the span length of flexural testing.

Span length [mm]	Flexural strength [3PB, MPa]	Deflection [mm]		Stiffness [N/mm]	Strain energy [MPa]	Flexural modulus [GPa]
		Experimentally measured [mm]	Theoretically calculated [mm]			
40	298.0 ± 34.7	1.56 ± 0.18	2.28	7.99	2.63	100.7
60	273.6 ± 43.4	3.92 ± 0.59	4.47	1.97	3.91	83.8
80	272.9 ± 31.9	7.16 ± 0.83	7.92	0.73	5.07	79.6
100	249.4 ± 31.1	10.33 ± 1.29	11.31	0.4	4.52	78.7
120	213.9 ± 27.3	13.28 ± 1.82	13.97	0.22	4.40	74.8
140	191.5 ± 15.7	16.15 ± 1.36	17.00	0.14	3.92	75.6

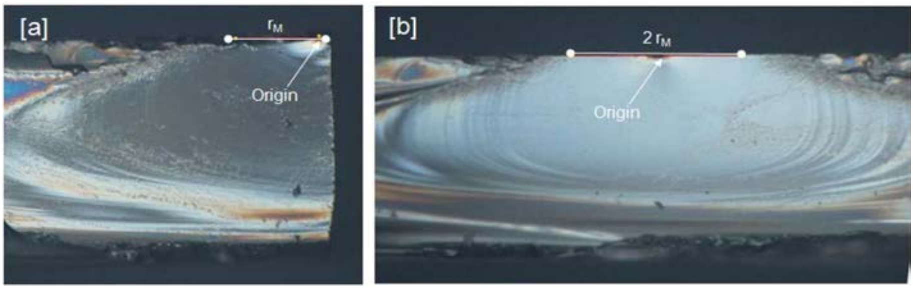

Fig. 2. Fracture surface with a fracture origin and a mirror radius. [a] edge origin, [b] surface origin.

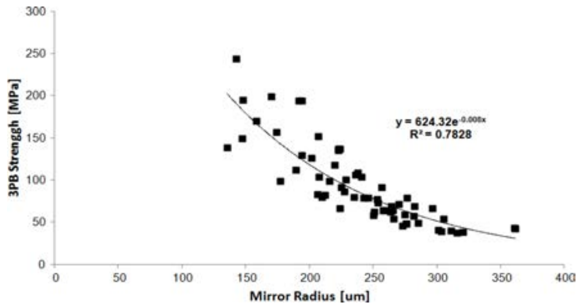

Fig. 3. Plot of the strength data versus the mirror radius; measured with all samples (60 mm, 80 mm, 100 mm, 120 mm).

and it indicates that the flexural strength of 0.55 t glass is in the range of 270 to 300 MPa.

In order to look into the correlation between the bending strength and the mirror strength, we carried out the fracture analysis with the broken samples. All data without classification in terms of the span length were used for plotting and the results were presented in Fig. 3. The mirror radius increased with decreasing the bending strength and the relation was the most likely to be nonlinear.

For calculating the mirror constant, Figure 3 was replotted as shown in Fig. 4(a). The plot gave a fairly linear relation and the mirror constant calculated from the slope was 55.83 MPa $\cdot$ (mm)$^{1/2}$. It was quite out of expectation because Gulati et al. reported the mirror constant for 0.7 ~ 1.1 t EXG glass is 65.3 MPa $\cdot$ (mm)$^{1/2}$ [5]. To find a relation to the previous report, the data point was categorized according to the span length and the data was plotted separately as seen in Fig. 4(b). The results did not show a consistency or tendency to the span length. However it was revealed that the values were varied in the range of 45.1 MPa $\cdot$ (mm)$^{1/2}$ to 67.4 MPa $\cdot$ (mm)$^{1/2}$ and this range included the mirror constant reported by Gulati's group. The interesting point is that the mirror constant looks like to have an agreement with Gulati's report when the span length decreased. We are thinking that such a difference could be based on the experimental condition because Gulati's group used 50 × 50 mm sand abraded samples for the biaxial strength (load ring diameter of 12.7 mm and support ring diameter of 25.4 mm). Our results carefully suggest that the mirror constant has a dependence of measurement condition especially in the span length (or displacement).

The mirror constant, A = 55.83 MPa $\cdot$ (mm)$^{1/2}$ obtained from Fig. 4(a) was applied to equation (4) to calculate the mirror strength. As presented in Table 2, it was observed that the mirror strength was directly proportional to the bending strength even though the whole of the mirror strength was low about 50 ~ 60 MPa compared to the flexural strength. In the same way, the mirror constants obtained from Fig. 4(b) were applied to equation (4) to observe the mirror strength according to the span length. With decreasing the span length, the difference between the flexural strength and the mirror strength was getting decreased, 68.0, 97.7, 21.7, and 14 MPa respectively. This result indicates that the equation (4) needs a constant "*C*" to correct the mirror strength and it should be forced to bigger for correcting the large deflection. To sum the results up, those results proved that there was a correlation among the span length, the

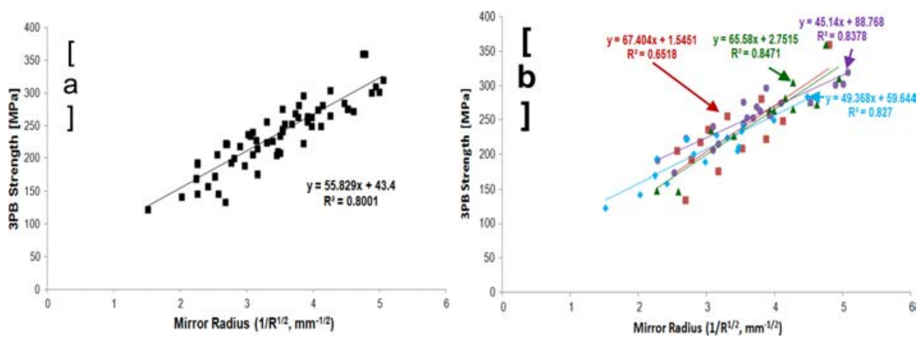

Fig. 4. Plot of the strength data versus the [a]mirror constant calculated with all data points, [b] mirror constant calculated as a function of the span length (60 mm, 80 mm, 100 mm, 120 mm).

Table 2. Comparison between the bending strength and the mirror strength as a function of span length.

Span length [mm]	Flexural strength [3PB, MPa]	Mirror strength (1)		Mirror strength (2)	
		Mirror strength [MPa]	Mirror constant [MPa(mm)$^{1/2}$]	Mirror strength [MPa]	Mirror constant [MPa(mm)$^{1/2}$]
60	273.6 ± 43.4	215.1 ± 42.48	55.83	259.6 ± 51.28	67.4
80	272.9 ± 31.9	213.9 ± 40.85	55.83	251.2 ± 47.99	65.6
100	249.4 ± 31.1	187.9 ± 55.09	55.83	151.7 ± 44.49	45.1
120	213.9 ± 27.3	164.4 ± 30.27	55.83	145.48 ± 26.78	49.4

Table 3. Mirror constant according to the span length and fracture origin.

		Span length [mm]			
		60	80	100	120
Mirror constant, MPa · mm$^{1/2}$ (MPa · m$^{1/2}$)	Surface origin	75.8 (2.40)	56.0 (1.77)	46.6 (1.47)	44.8 (1.42)
	Edge origin	41.8 (1.32)	58.1 (1.84)	46.3 (1.46)	53.4 (1.69)
	All	67.4 (2.13)	65.6 (2.07)	45.1 (1.43)	49.4 (1.56)

flexural strength and the mirror strength.

To see the effect of fracture origin on mirror constant, the data was separated into surface and edge origin and the results were summarized in Table 3. In case of the specimens with the surface origin, the mirror constant seemed to have a dependence of the supporting span length. The mirror constant increased with decreasing the span length. In case of the specimens with the edge origin, on the other hand, there was no tendency according to the span length and were varied from 40 to 58 MPa · (mm)$^{1/2}$.

Effect of the supporting span length of flexural testing on glass properties was carefully studied by measuring a 3-point bending strength and by calculating the related properties such as stiffness, strain energy and flexural modulus. We reported that the flexural strength and the depth of deflection had a linear relationship in terms of the span length. The stiffness and the flexural modulus increased non-linearly with decreasing the span length and the strain energy had a maximum value at 80 mm span length. We also mentioned that the transition from shear fracture to flexural fracture was happened when the ratio (the span length/the depth of displacement) was around 11 as shown in Figure 1.

Fracture analysis to observe the correlation between the bending strength and the mirror radius presented that the mirror radius was the most likely to be nonlinear to the mirror radius and the mirror constant was around 55.83 MPa · (mm)$^{1/2}$. This value was quite out of our expectation because Gulati reported the mirror constant for 0.7 ~ 1.1t EXG glass is 65.3 MPa · (mm)$^{1/2}$ at previous study. To figure out the reason why there was a difference, the mirror constant was calculated again in terms of the span length as shown in Fig. 4[b]. We showed that the range of the mirror constant was varied from 45.1 to 67.4 MPa · (mm)$^{1/2}$ according to the span length and this range included the value reported by Gulati's group. Recently, Dugnani's group analyzed the previous studies based on mirror constant and summarized the result in their paper [11]. They reported that the mirror constants were varied as a function of the glass system, the glass thickness as well as the test condition. The important point should be noted at there that even though the similar glass system was employed for the experiment, the mirror constant could be varied from 1.1 MPa · (m)$^{1/2}$ to 2.23 MPa · (m)$^{1/2}$ depending on the author [10, 11]. Another thing should be pointed is that the equation (4) needs a constant "*C*" to correct the difference between the flexural strength and the mirror strength, and the large value of correction constant was required especially to correct samples with large deflection.

Conclusions

This study reported the effect of the supporting span length by measuring a 3-point bending strength. The mechanical properties of glass such as stiffness, strain energy and flexural modulus had a dependence of the span length. The transition point indicating from shear to flexural fracture was observed when the ratio between the span length and the depth of the displacement was around 11. The mirror radius was inversely proportional to the bending strength and the relation was the most likely to be nonlinear. The mirror constant was also fluctuated in terms of the span length as well as the fracture origin, and the values were in the range of 45.1 MPa · (mm)$^{1/2}$ to 67.4 MPa · (mm)$^{1/2}$.

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