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Window glass design in light of weathering effect

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ABSTRACT

When severe wind events occur, failure of window glass can be observed quite frequently. Although the main cause of this failure is believed to be wind-borne debris, failure due to wind pressure is also relatively common and numerous studies were performed on estimating window glass plate strength under wind loading. With respect to the estimation of glass strength, a proper determination of initial glass strength, which is the strength before glass is loaded, is important and the weathering effect is known to affect the initial glass strength.

Regardless its importance, few studies have previously been conducted on the weathering effect because a large number of in-service glass plates necessary to obtain statistically significant results can seldom be obtained in practice. However, due to the Great East Japan Earthquake, some buildings in the Faculty of Engineering, Tohoku University were severely damaged and a decision was made that they should be demolished and rebuilt. This allowed us to obtain a large number of in-service window glass plates from one of the buildings before it was demolished.

A coaxial double ring test was performed both on in-service glass plates from the destroyed building and on new plates. Thereby, the reduction of glass strength due to weathering effect was evaluated. By treating the obtained breakage strength as initial glass strength, glass strength was calculated by performing glass strength modeling, which considered the unique characteristic of glass plates (i.e., static fatigue). Finally, a fragility analysis was performed using the obtained wind load resistance in order to observe the weathering effect on wind speeds in design situations.

1. INTRODUCTION

One of the cladding materials which commonly fail during severe wind storms is window glass. Although numerous studies were performed on estimating window glass plate strength for wind loading, the weathering effect on glass strength has not been widely examined regardless of its importance.

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Glass plate failure is determined based on the relationship between the degree of crack growth and the magnitude of induced tensile stress on its surface. Crack growth on the glass plate surface is directly related to glass strength and it depends on factors such as the plate's surface condition and environment. The weathering effect is one of the most important factors affecting surface crack growth, namely, glass strength.

One of the reasons why the weathering effect has been rarely examined is believed to be because it is difficult to obtain a sufficiently large number of glass plates that have actually been installed on buildings for several years. The weathering effect is usually evaluated using the Weibull parameters (Weibull 1939) of initial glass strength obtained from glass samples assuming that a Weibull variate approximates the initial glass strength.

Among the limited number of previous studies, intensive studies on weathering effect were performed by researchers from Texas Tech University in 1980s (Beason 1980; Beason and Morgan 1984; Abbiassi 1981; Kanabolo and Norville 1985) and their results were reflected in the initial glass strength used for the calculation of load resistance in the North American window glass design. Although they utilized a large number of in-service glass plate samples from several different buildings, there is a doubt in their approach to obtain the initial glass strength. The Weibull parameters for initial glass strength were estimated not by performing the commonly performed coaxial-double-ring test but by conducting full-scale glass breakage test. This approach was probably adopted on account of the technology available at the time. In their estimation method, the Weibull distribution, which predicts the instantaneous failure probability, was used for the equivalent 60-sec constant stress, which can hardly be recognized as instantaneous. In addition, failure origin was needed to be identified in their method and this was performed by visual examination, which is likely to affect the accuracy and variability in the results.

To the authors' knowledge, Fink (2000) is the only study which dealt with weathered glass plate in Europe while Blank (1993) examined the strength reduction using glass samples with artificially induced homogeneous surface damage.

In 2011, the Great East Japan Earthquake occurred and some buildings in the Faculty of Engineering, Tohoku University were severely damaged. Since a decision was made that they should be demolished and rebuilt, we had an opportunity to obtain a large number of in-service window glass plates from one of the buildings and thereby to enrich the database of in-service window glass strength.

This paper presents results of coaxial double ring tests performed on new and in-service glass plates, which can be used for estimating the glass strengths. Furthermore, a fragility analysis is performed using the obtained glass strength in order to see the weathering effect on wind speed in design situations.

2. DEFINITION OF INITIAL GLASS STRENGTH

Glass is a unique material because it does not necessarily fail at a large stress level, unlike the common materials. Rather, it fails through a mechanism called static fatigue (Charles 1958), also sometimes called 'delayed failure' which is a time-dependent reduction of strength due to the combination of duration and magnitude of loading. This feature of glass has been recognized for more than 30 years (Minor 1981), and is well described by Brown's integral (Brown 1972; 1974),

$$DA_{crit} = \int_0^{t_f} [\sigma_a(t)]^n dt \tag{1}$$

where DA_{crit} is the critical damage accumulation, t_f is the failure time, $\sigma_a(t)$ is the time-dependent applied stress at the critical crack (i.e., the particular crack leading to failure) on a glass surface, and n is a constant (generally accepted to be 16 for soda-lime silicate glass). Eq. (1) means that glass failure occurs when the right-hands of Eq. (1) reaches its critical value.

In addition to Brown's integral, a simplified form of it has been introduced using a power law relationship between stress and applied pressure (Brown 1972; Dalgliesh and Taylor 1990; Kawabata 1996; Calderone 1999) so that,

$$DA_{crit}' = \int_0^{t_f} [p(t)]^s dt \tag{2}$$

where p is the applied load and s is a coefficient. A beneficial aspect of Eq. (2) is that it requires applied pressure instead of the stress induced at a crack; hence, the critical crack location on glass is not required for this calculation, as it is for Eq. (1). However, the values of s for specific glass plates differ due to the p - σ_a relationship, which is non-linear and varies at each location on any given plate. Thus, it is often presented as a range for the various parameters (plate dimensions, glass type, etc.) which affect the p-σ_a relationship.

Reflecting this characteristics, load resistance, *LR*, used for window glass design needs to be specified as glass strength, *S*, calculated considering the strength reduction due to the static fatigue during the assumed design period from initial glass strength, S_i. This means the proper estimation of initial glass strength is quite important for the determination of *LR*. While 'initial glass strength' for new glass refers to glass strength at installation or at the end of the production line, 'initial glass strength' for in-service glass refers to the glass strength before a coaxial double ring test is performed in the current study. This means possible strength reduction during the uninstallation of window plates or the cutting process from glass samples to small specimens is assumed to be included in the initial glass strength although unexpected strength reduction was minimized by carefully treating glass plates.

Initial glass strength, S_i, is often approximated by the Weibull distribution:

$$P_f = 1 - \exp\left\{-\left(S_i/\theta_0\right)^{m_0}\right\} \tag{3}$$

where P_f is failure probability, θ_0 is a measure of location, m_0 is a measure of dispersion. Larger θ_0 means larger initial glass strength and larger m_0 means smaller variation of initial glass strength. In the current study, the weathering effect is evaluated using the Weibull parameters following the approach outlined in previous studies.

3. COAXIAL DOUBLE RING (CDR) TEST

3.1 Test specimen

Window glass samples were obtained from a research building of the Department of Engineering and Architecture, Tohoku University, which was severely damaged due to the Great East Japan earthquake in 2011(

Figure 1). Although this 9-story building was built in 1969, all the windows were replaced with new ones in 2000. Window glass samples used for the current analysis were uninstalled from the 1st floor of this building in 2012.

The window glass samples are insulated glazing windows (glass plate + air gap + glass plate) and the thickness of annealed glass plate is 5 mm. We have named each glass plate surface as A, B, C and D as shown in

Figure 2 for convenient. After all the window glass samples were delivered to an experimental laboratory, glass plates were separated from the frames and all glass plate samples were examined by exposing ultraviolet radiation in order to determine the 'air' and 'tin" sides. Since 'tin' side is believed to be weaker than 'air' side, we have selected glass samples whose 'tin' side surface was faced air gap (B or C) and those whose 'tin' side surface was faced outside (D) (we denote them 'Air' and 'Outside', respectively). The samples were cut into 24 cm square specimens. After eliminating all the specimens which received any obvious damage during the cutting process, we could obtain in total 94 and 100 specimens for Air and Outside, respectively. In order to evaluate the degree of weathering, 40 of 18 cm square specimens from new annealed monolithic glass plates (thickness of 3 mm) were also prepared for testing, assuming that the calculated initial glass strength does not depend on the thickness of glass plates.

Figure 1: Former research building of Department of Civil Engineering and Architecture, Tohoku University

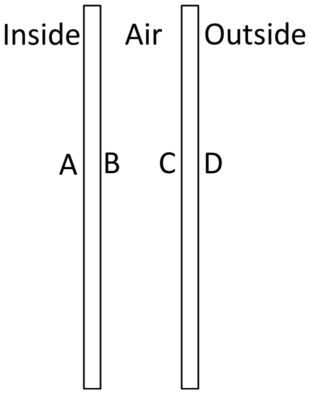


Figure 2: Detail of insulated glazing window samples

3.2 coaxial double ring (CDR) test

In coaxial double ring tests, glass specimen was placed on a supporting ring and was loaded by means of a loading ring arranged concentrically relative to the supporting ring (

Figure 3). With this testing method, uniform stress can be applied in both circular and radical directions inside the loading ring and the specimen edge conditions do not affect the failure stress. The glass specimen was loaded at a rate of 2 +/- 0.4 (MPa/sec) following EN1288-5 (2000) until failure. The specimen whose fracture origin was outside of the loading ring was eliminated and eventually, we could obtain 25, 72 and 61 failure loads (W_f) for new, Air and Outside specimens, respectively. Failure stress (σ_f) was calculated from W_f using the following equation:

$$\sigma_f = 0.67 W_f / h^2 \tag{4}$$

where h is specimen thickness.

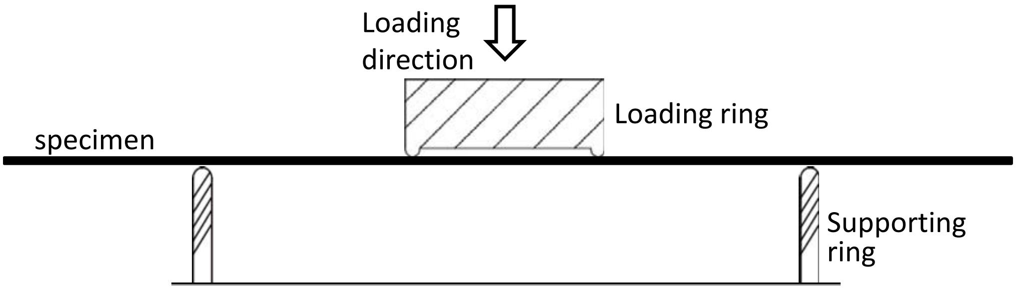
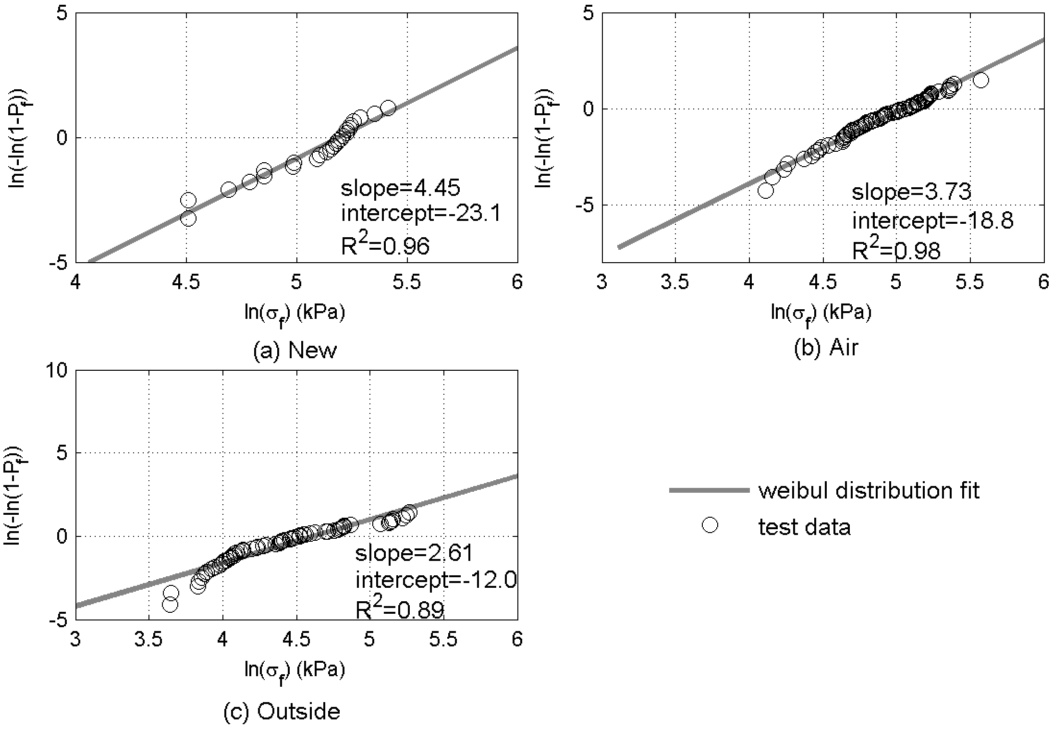


Figure 3: Image of coaxial double ring test

3.3 Test results

Figure 4 shows the obtained failure stress results, σ_f, and their Weibull distribution parameters calculated using the maximum likelihood method. Based on the root mean square value (R^2) presented in each figure as well as the correspondence between test data and distribution fit, a choice of Weibull distribution to model σ_f seems appropriate, as have been mentioned in previous studies (Brown 1972; Kawabata 1996; Haldimann 2006).

Table 1 presents the mean and coefficient of variance (COV) of σ_f as well as the Weibull parameters (θ_{ring}, m_{ring}) for the glass surface area size (A) of 1 m^2 (A_0). For comparison, the test results obtained by Kawabata (1996) using new monolithic annealed glass specimen (h =6mm) are also included. θ_{ring} of the present new glass specimens corresponds well with those of Kawabata regardless of the small number of specimen. The difference in m_{ring} between two studies is believed to be directly related to the difference of the number of specimen used in the tests. By comparing the results from new glass specimens and those from in-service glass specimens, it is clear that the strength was reduced and the variation of the strength was increased due to weathering.



(a) New

(b) Air

(c) Outside

Figure 4: Failure stress data from coaxial double ring test fitted to the Weibull distribution

Table 1: results of coaxial double ring test

	# of specimen	σ_{f_ave} (MPa)	σ_{f_COV} (-)	θ_{ring} (A_0) (MPa)	m_{ring} (-)
New	25	164	0.22	43.5	5.88
Air	72	141	0.30	26.1	3.73
Outside	61	90	0.46	5.9	2.34
Kawabata (1996)	~70	(-)	(-)	37.8 - 42.5	6.33 - 6.77

4. CONVERSION TO INITIAL GLASS STRENGTH

If the CDR test is performed in the condition where the strength reduction due to static fatigue cannot occur, called inert condition, the Weibull parameter for failure stress, σ_f, is the same as the ones for initial glass strength. According to Haldimann (2006), the inert condition can be achieved relatively easily by conducting CDR test at very rapid stress rates (around 20 MPa/sec) or applying hermetic coating on specimens. Unfortunately, the inert condition was not created neither in the present nor Kawabata's CDR tests; hence, the Weibull parameters for initial glass strength needed to be estimated by eliminating the strength reduction during the CDR test from the Weibull parameters for σ_f. This was performed using the method suggested by Haldimann (2006).

Haldimann (2006) presented the life prediction model which can calculate the time-dependent failure probability for a given action history, which was derived based on fracture mechanics and the theory of probability. Furthermore, the simplified model for the loading condition of CDR test was obtained as:

$$P_f(\sigma_f) = 1 - \exp\left\{-\left(\sigma_f / \theta_{ring}\right)^{\beta_{ring}}\right\} \tag{5}$$

where θ_{ring} and m_{ring} are defined as:

$$\theta_{ring} = \left[U(n+1)\dot{\sigma}\theta_0^{n-2}\right]^{\frac{1}{n+1}} (A/A_0)^{-1/\beta_{ring}} \eta_b^{\frac{-n}{n+1}} \tag{6}$$

$$\beta_{ring} = \frac{m_0(n+1)}{n-2} \tag{7}$$

In Eq. (6), n is exponential crack velocity parameter and η_b is biaxial stress correction factor. U is defined as

$$U = 2K_{IC}^2 \big/ [(n-2) \cdot v_0 \cdot Y^2 \cdot \pi] \tag{8}$$

where K_{IC} is fracture toughness or critical value for stress intensity factor (K_I), v_0 is linear crack velocity parameter and Y is geometric shape factor. From Eqs. (6) and (7) with η_b =1, the Weibull parameters for initial glass strength, θ_0 and m_0, can be obtained using the Weibull parameters for σ_f (i.e., θ_{ring}, m_{ring}):

$$\theta_0 = \left[\frac{(\theta_{ring}(A/A_0)^{1/\beta_{ring}})^{n+1}}{U \cdot (n+1) \cdot \dot{\sigma}}\right]^{1/(n-2)} \tag{9}$$

$$m_0 = \beta_{ring}\frac{n-2}{n+2} \tag{10}$$

In the equations above, Haldimann used the following equation in order to relate K_I, Y, nominal tensile stress normal to the crack, σ_n, and the length or another characteristics dimension of the crack, C, with Y=1.12:

$$K_I = Y \cdot \sigma_n \cdot \sqrt{\pi \cdot C} \tag{11}$$

However, according to previous studies (Evan and Fuller 1974; Evan and Weiderhorn 1974; Weiderhorn 1974; Reed and Simiu 1984; Mencik 1992; Fischer and Collins 1995; Overand 2007), the following expression seems to be more generally employed with the same value of Y (=1.12):

$$K_I = Y \cdot \sigma \cdot \sqrt{C} \tag{12}$$

where σ is the nominal stress (tensile, shear, etc). When the crack growth is considered, normal stress to the crack is more dominant than the shear stress and hence, Eq. (12) can be used for σ_n. Eqs. (5), (6), (7), (9) and (10) were modified using Eq. (12) instead of Eq. (11). This change appears in the calculation of U in Eq. (8) while Eqs. (9) and (10) remain the same:

$$U = 2K_{IC}^2 \big/ [(n-2) \cdot v_0 \cdot Y^2] \tag{13}$$

In order to obtain θ_0 and m_0 using Eqs. (9) and (10), the values of Y, K_{IC}, n, v_0 need to be assumed. Y =1.12 and K_{IC}=0.75 have been selected by many researchers for the half-penny shaped crack induced at the surface of the glass and for soda-lime silicate glass, respectively.

The crack growth coefficients, n and v_0 , need to be obtained from experiment and are known to be sensitive to various factors such as temperature, humidity, loading rate, material and so on. However, the detailed information on these factors used in the test is not always available. Therefore, unless the crack growth coefficients, which have sufficient accuracy and are stable for the CDR test condition, are obtained, it is difficult to carry out the estimation of initial glass strength precisely. Only a few sets of crack growth coefficient data with enough information are available and Table 2 shows a summary of these available data obtained under conditions relatively similar to those used for the current CRD test. Although the values in Table 2 vary among studies, it was decided to use n=16 and v_0 =0.01(m/s) in this study. n =16 was selected since it has been widely used in previous studies (Brown 1972; Abiassi 1981; Haldimann 2006). With respect to v_0, 0.01 (m/s) was selected based on the following two reasons. First, in order θ_0 not to be smaller than θ_{ring} for the current test results, v_0 needs to be larger than 0.01 (m/s). Second, for design purpose, it is safer to assume smaller v_0, which prevents overestimating θ_0 using θ_{ring}. The authors are aware of the fact that more careful consideration is necessary for the selection of v_0. Consideration of this problem is an on-going task since v_0 affects the resulting value of θ_0 and eventually glass strength, S, significantly. However, the current study focuses on the effect of weathering by comparing S from new glass samples and those from in-service glass samples, and it was confirmed that the difference in S between these samples does not change greatly regardless of the magnitude of actual S. Thus, subsequent analysis was carried out with n=16 and v_0 =0.01(m/s).

Table 2: crack growth coefficient from previous studies

	Loading type	RH (%)	T (C^o)	n (-)	v_0 (m/sec)
Wiederhorn and Bolz (1970)	Step-up loading	100	25	14.98 17.84	0.009 0.01
Evan and Fuller (1974)	Static loading Cyclic loading	(-)	(-)	25.15 25.38	0.02 0.04
Wiederhorn (1974)	(-)	50	20	19.69	0.004
Dwivedi and Green (1995)	(-)	65	27	21.8	0.0026
Kawabata (1996)	(-)	(-)	(-)	16	0.01
Haldimann (2006)	Ramp loading	(-)	(-)	16	0.00001

5. INITIAL GLASS STRENGTH

The Weibull parameters for initial glass strength obtained in a manner explained in the previous section are presented in Table 3. For comparison, $\theta_0(A_0)$ and m_0 values calculated from the CDR test results performed by Kawabata (1996), Sedlacek et al. (1999) and Fink (2000) are also included.

In the case of $\theta_0(A_0)$ for new glass plates, present result (66.83 MPa) is similar to those obtained by Kawabata (57.77, 67.28 MPa) and by Haldimann (67.6 MPa). Especially, a good correspondence with the data obtained by Kawabata who used quite a larger number of samples assures the quality of the present CDR test results.

θ_0 from Sedlacek et al. (1999) takes quite larger value than the others. Since the loading rate used by Sedlcek et al. (1999) for their CDR tests is the same as the one used for the present study, this difference is unlikely to be caused by the assumed values of n=16 and v_0 =0.01(m/s). In addition, θ_{ring} obtained by Sedlacek et al. (1999) is larger than those obtained by others; thus, the cause of this large difference in θ_0 may be the condition/type of specimens or unknown details of the CDR test. The reason is not clear at this point.

In terms of m_0, the value obtained by Haldimann is larger than the others and it is uncertain whether its cause is faster loading rate, small number of specimen, or something else entirely.

In Section 3.1, we have assumed that θ_0 and m_0 do not depend on the thickness of specimen. From the results presented in Table 3, this assumption is likely to be true and the further analysis was conducted with this assumption.

Table 3: The Weibull parameter for initial glass strength ($\theta_0(A_0)$and m_0)

	Surfaces condition	$\dot{\sigma}$ (MPa/s)	# of specimen	h (mm)	θ_0(A$_0$) (MPa)	m_0 (-)
Present	New	2.0	22	3	66.83	4.84
	Air	2.0	72	5	35.39	3.07
	Outside	1.9	61	5	5.90	1.93
Kawabata (1996)	New	1.4	~70	6	57.77	5.21
	New	1.2	~70	6	67.28	5.58
Sedlacek et al. (1999)	New	2.0	(-)	N/A	95.46	4.94
Haldimann (2006)	New	21	10	6	67.6	7.20
Fink (2000)	weathering	2.0	(-)	N/A	31.60	3.76

With respect to the effect of weathering, θ_0 obtained for the specimen exposed outside (Outside) is 1/10 of the one for the new glass. 10 years, which is relatively short compared to the design lifetime of an average building, is found to be long enough to reduce the glass strength. Surprisingly, θ_0 obtained for the specimens exposed air gap (Air), where no external factor is believed to contribute to weathering, is less than half of the one for the new glass.

The result from Fink (2000) is the only reference which performed CDR test with weathered glass plates. Since the detail of the specimen is unknown, a comparison of θ_0 from Fink (2000) may not be meaningful. However, the tendency of having smaller m_0 for weathered glass is similar at least.

6. CALCUALTION OF GLASS STRENGTH

As explained in Section 2, the initial glass strength is the key parameter for the calculation of glass strength, S. In order to examine the effect of weathering on S, it was calculated using the previously established glass strength modeling (Gavanski and Kopp 2011) with the initial glass strength obtained in Section 5. This modeling can determine glass strength considering static fatigue, using fracture mechanism under several loading types including dynamic loading. The modeling was validated by comparing full-scale glass breakage tests performed under 6 different loading patterns. A common set of inputs necessary for the modeling (specifically, v_0, n and K_{Ii}), which are applicable to all 6 loading cases in order to match the modeling results closely to test results, were not determined. Hence, all the 'best sets' for each loading case were employed in this calculation and the final output (i.e., S) is presented as a possible range. For further details, the reader is referred to Gavanski and Kopp (2011). The modeling was conducted on 1 x 1 x 0.006 (m), monolithic annealed glass plates, which are simply supported at their edges, under 10-sec static loading for the current analysis.

6.1 Weathering effect on glass strength

Glass strength obtained under 10-sec static loading were calculated using the initial glass strength of new glass ($\theta_0(A_0)$=66.83(MPa), m_0=4.48, denoted as 'New'), the one of glass plate faced air space ($\theta_0(A_0)$=35.90(MPa), m_0=3.07, denoted as 'Air'), and the one of glass plate faced outside ($\theta_0(A_0)$=5.90(MPa), m_0=1.93, denoted as 'Outside').

Their cumulative distribution functions (CDFs) are presented in Figure 5. The right figure in Figure 5 shows the CDF at around the failure probability (P_f) utilized in the design codes (1/1000 for Notification No. 1458 of the Ministry of Construction, Japan and 8/1000 for ASTM E1300 (2009) in US and the CGSG standard (1989) in Canada). As expected, S becomes larger when it is calculated with larger θ_0. However, the difference in calculated S at a certain failure probability is not necessary corresponding to the one of θ_0. For example, at P_f = 8/1000, S of New is 29-31% and 2.5-3.1% of S of Air and Outside, respectively while θ_0 of New is 54% and 9% of θ_0 of Air and Outside, respectively. This is on account of m_0; hence, the present results indicate the importance of considering not only θ_0 but m_0 when the weathering effect is considered for glass strength estimation.

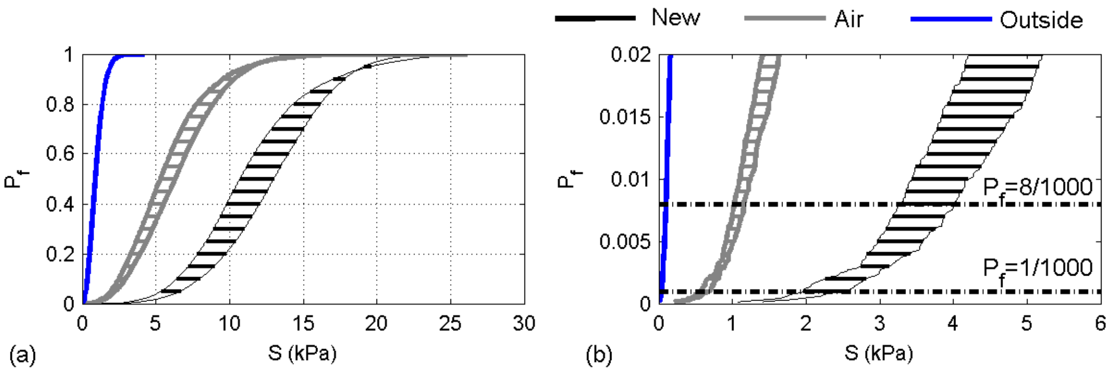


Figure 5: CDF of glass strength

6.2 Effect of m_0 on glass strength

Since it was found that the effect of $m_0$on glass strength is not minor, this effect was further examined by calculating glass strength with fixed θ_0 value but with m_0 values in the range of 3 to 20. The results are shown in Tables 4 and 5. It is clear that larger m_0 results in larger S and the effect of different m_0 on S is more apparent for smaller θ_0. Thus, the estimation of m_0 needs to be carefully performed, especially for in-service glass plates.

Reflecting the current results, the Weibull parameters employed in North American window glass design were examined. The load resistance (*LR*) in ASTM E1300 and the CGSG standard were calculated using the glass failure prediction model (GFPM) introduced by Beason and Morgan (1984). In the case of GFPM, the Weibull parameters for the initial glass strength obtained in the format of the equivalent t_{ref}-sec constant stress are necessary. The Weibull parameters of $\theta_{0,\text{code}}(A_0)$=32.08 (MPa) and $m_{0,\text{code}}$=7 are utilized in the calculation of *LR* for both design codes although different t_{ref} is utilized in ASTM E1300 and the CGSG standard (This issue is discussed in more detail elsewhere (Haldimann 2006; Gavanski and Kopp 2011)). According to Beason and Norville (1990), the values for both parameters were selected considering the strength of glass that has undergone several years of in-service conditions. Specifically, a value of $m_{0,\text{code}}$ associated with a COV of 18% to 22% was selected.

In order to compare $m_{0,\text{code}}$ and m_0 obtained from CDR tests which use constant stress rate loading, a conversion is necessary. This was accomplished using the conversion method suggested by Haldimann (2006). As a result, $m_{0,\text{code}}$=7, used in the North American design codes, was converted to m_0=6.13.This value is larger than m_0 values for new glass listed in Table 3 (4.8-5.6, except the result from Haldimann), meaning that the North American design codes assume less variability in initial glass strength for the calculation of *LR* than the one for new glass plates. It may have been an intention of code committees to choose a large value for $m_{0,60\text{sec}}$, considering the use of in-service glass strength information for the estimation of *LR*, and it is also true that the number of available reference was limited and difficult to choose the parameters. However, the current results indicate that the calculated *LR* may have been overestimated than the expected values, and this may have resulted in unsafe standards being set for North American window glass design.

Table 4: Glass strength at P_f =1/1000 and 8/1000 estimated with $\theta_0(A_0)$=66.83 (MPa)

	P_f=1/1000		P_f =8/1000	
	S (MPa)	Ratio relative to $S(m_0=20)$	*S* (MPa)	Ratio relative to $S(m_0=20)$
m_0=3	0.96-1.19	16-17%	1.84-2.12	25-29%
m_0=5	1.97-2.59	35%	3.28-4.02	48%
m_0=7	2.95-3.97	53-54%	4.38-5.59	67-68%
m_0=20	5.60-7.41	N/A	6.43-8.33	N/A

Table 5: Glass strength at P_f =1/1000 and 8/1000 estimated with $\theta_0(A_0)$= 35.90 (MPa)

	P_f =1/1000		P_f=8/1000	
	S (MPa)	Ratio relative to $S(m_0=20)$	*S* (MPa)	Ratio relative to $S(m_0=20)$
m_0=3	0.59-0.71	21-24%	1.03-1.16	30-35%
m_0=5	1.12-1.38	42-45%	1.68-2.00	52-57%
m_0=7	1.51-1.86	56-61%	2.09-2.57	67-71%
m_0=20	2.48-3.30	N/A	2.95-3.83	N/A

7. WEAHTERING EFFECT ON DESIGN WIND SPEED

Thus far, the weathering effect has been presented in terms of glass strength. Glass strength (or initial glass strength) is how the previous studies have demonstrated their results. The present study takes a further step to examine how the weathering effect impacts the actual design situation by performing a fragility analysis using the design wind loads specified in the AIJ Recommendations for Loads and Buildings in Japan (AIJ Recommendations 2004).

7.1 Calculation method

Fragility analysis was performed on a monolithic, annealed glass plate (1 x 1 x 0.006 m) using Rackwitz-Fiessler procedure (Nowak and Collins 2000). The limit state function, *z*, for a glass plate subjected to uniform wind load can be written as

$$z = R - W \tag{14}$$

where *R* is glass capacity (glass strength) and *W* is wind load. Failure of a plate occurs when $z < 0$.

Rackwitz-Fiessler procedure requires the knowledge of the probability distributions for all the variables involved.

With respect to *R*, the modelling method introduced in Section 6 was utilized with the three sets of the Weibull parameters for initial glass strength obtained from the current study listed in Table 3. When glass strength was calculated in Section 6, the crack growth parameters (v_0, *n*) with which the simulated results correspond well with the results from full-scale glass breakage test were employed. However, larger v_0 needs to be assumed for safer design, thus the values of v_0=6 (mm/s) and *n*=16 were employed in the present analysis following the recommendation of Haldimann (2006).

For the present analysis, it was found that *R* can be modeled as a Weibull variate based on Akaike Information Criterion (AIC) (Akaike 1974) and Bayesian Information Criterion (BIC) (Schwarz 1978), rather than normal and lognormal variates. The use of the Weibull distribution for glass strength is consistent with previous studies (e.g., Simiu and Reed 1983; Kawabata 1996). The Weibull parameters for *R* were calculated from the three set of glass strength modeling results (denoted as Glass A, B, C for those calculated with $\theta_0(A_0)$=66.83(MPa) & m_0=4.48, $\theta_0(A_0)$=35.90(MPa) & m_0=3.07, $\theta_0(A_0)$=5.90(MPa) & m_0=1.93, respectively).

In terms of wind load, *W*, the following equation defined in the AIJ Recommendations is employed:

$$p_{AIJ} = \frac{1}{2}\rho\left(U_0 K_D E_r E_g k_{rW}\right)^2 \cdot \left(\hat{C}_{pe} - C*_{pi}\right) \tag{15}$$

where ρ is the air density(1.22 kg/m^3), U_0 is the basic wind speed(m/s), K_D is the wind directionality factor, E_r is the exposure factor , E_g is the topographic factor, $k_{r,w}$ is the return period conversion factor, and $\hat{C}_{pe}$ and C^*_{pi} are the external and internal pressure coefficients, respectively. Among all, ρ, E_g and k_{rW} were assumed to be deterministic and were set to be 1.22, 1 and 1, respectively. The others were treated as variables and their nominal value were assumed to be those listed in the AIJ Recommendations (Table 6). The nominal value of E_r was calculated assuming low-rise buildings in the roughness terrains of II, III and IV defined in the AIJ Recommendations. The nominal value of $\hat{C}_{pe}$ was assumed to be negative value since the negative $\hat{C}_{pe}$ value has larger magnitude than the positive one. With respective to C^*_{pi}, the AIJ Recommendations provide a choice between 0 or -0.5. Since C^*_{pi} =0 produces larger nominal wind force with negative $\hat{C}_{pe}$, it was set to 0.

The distribution information for K_D, E_r, $\hat{C}_{pe}$ were taken from the previous studies which performed fragility analysis using the wind load information of ASCE7 (Ellingwood et al. 2004; Lee and Rosowsky2005; Li and Ellingwood 2006). The wind load in ASCE7-10 is defined as:

$$W = 0.613 \cdot K_z \cdot K_{zt} \cdot K_d \cdot I \cdot V^2 \cdot (GCp - GCp_i) \tag{16}$$

where K_z is the velocity pressure exposure factor, K_{zt} is the topographic factor, K_d is the wind directionality factor, I is the importance factor, V is the basic wind speed, GCp and GCp_i are the external and internal wind pressure coefficients, respectively. Since K_D in the AIJ Recommendations generally corresponds to K_d in ASCE7-10, distribution information necessary for Rackwitz-Fiessler procedure (the mean-to-nominal ratio, COV and fitted distribution) of K_d in ASCE7-10 was employed as those of K_D, as shown in

Table 6. The same treatment was performed for E_r and $\hat{C}_{pe}$ using the information of K_z and GCp, respectively. The appendix 6.6 of the AIJ Recommendations mentions distribution information for some variables in Eq. (16) briefly, and COV for $E_H(=E_r*E_g)$ at 5m height and $\hat{C}_{pe}$ are suggested as 0.13 and 0.2, respectively. Although the former corresponds well with the COV of E_r at terrain II, the latter is larger than the one in

Table 6.

Table 6: Wind load statistics

		Nominal value	Mean/nominal	COV	distribution
K_D		1	1.05	0.16	Normal distribution
E_r	II	0.9	0.96	0.14	
	III	0.79	1.01	0.19	
	IV	0.69	1.01	0.19	
$\hat{C}_{pe}$		-3	0.95	0.12	

Since the wind load in the AIJ Recommendations does not take the form of equivalent static load necessary for window glass design, wind load obtained from Eq. (15), p_{AIJ}, cannot be used directly in Eq. (14). According to Gavanski (2012) which examined whether the use of p_{AIJ} is appropriate to be used as design load for window glass design (DL), p_{AIJ} can be used as DL without underestimation by multiplying by 1.3.

Considering all the information mentioned above, the limit state function, z, can be re-defined as:

$$z = R - 1.3 \cdot 0.5 \cdot 1.22 \cdot \left(U_0 \cdot K_D \cdot E_r\right)^2 \cdot \hat{C}_{pe} \tag{17}$$

The reliability index, β, was calculated for different standard wind speed, U_0. The failure probability, P_f, has a relationship with β as

$$P_f = \Phi(-\beta) \tag{18}$$

where $\Phi(\bullet)$ denotes the standard normal distribution function.

7.2 results

Figure 6 shows the calculation results for different terrain conditions. In order to calculate the glass strength, S, using the glass strength modeling, various sets of distribution information for K_{li} had to be considered and this resulted in various S as explained in Section 6. Hence, the results are presented as a range in

Figure 6. Although the design reliability index is not selected in Japanese window glass design, the value of more than 2.0 is generally recommended (Flat Glass Manufactures Association of Japan 2001). β=2.0 corresponds to P_f of 2.28% from Eq. (18). In addition, the maximum basic wind speed, U_0, in the AIJ Recommendations is 50 m/s; hence the results are presented in these ranges.

When glass design is performed with R calculated from the weakest initial glass strength (Glass C), P_f reaches 2.28% when $U_0$is less than 20 m/s. Considering the fact that the minimum U_0 listed in the AIJ Recommendations is 30 m/s, this result indicates that the use of Glass C cannot achieve β=2.0 anywhere in Japan. Thus, when weaker glass plates are selected by considering the weathering effect or assuming slower crack growth for the estimation of initial glass strength, it is necessary to choose the glass plate type or size (thicker and smaller glass plate) which has stronger initial glass strength than the one of 1 x 1 x 0.006 m monolithic annealed glass plate.

Figure 6 indicates that β=2.0 can be achieved by using Glass B except in terrain II since U_0 for most of the regions in Japan are 30 – 40 m/s. This means that with 1 x 1 x 0.006 m monolithic annealed glass plate, it is possible to cover the variability in glass strength due to weathering effect or crack growth coefficient to a certain degree.

If the window design is performed with Glass A, P_f is less than 0.5% at U_0 of 50m/s, which is the maximum wind speed specified in the AIJ Recommendations for Japan, in any terrain conditions. This result means if both weathering effect and variation of crack growth speed are not considered in the selection of initial glass strength, it is possible to use glass plate type or size (thinner and larger glass plate) whose strength is smaller than the one of 1 x 1 x 0.006 m monolithic, annealed glass plate.

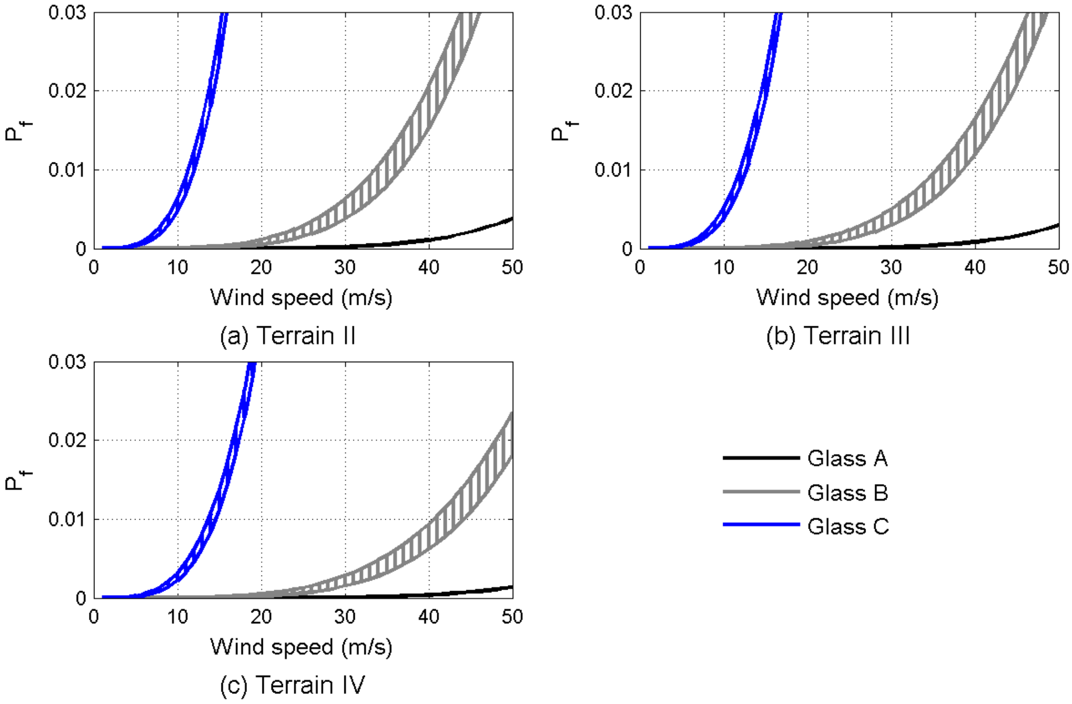


Figure 6: Fragility curves for wind speed,,

8. CONCLUSIONS

With an opportunity to obtain a larger number of in-service window glass samples, the weathering effect on glass strength was examined. The results indicate that a period of10 years is long enough to reduce the glass strength significantly and the glass strength reduction can occur even when the glass plates are not faced to the outside environment. Various input data are necessary in order to estimate the initial glass strength based on the glass failure strength obtained under non-inert condition and affect the calculated initial glass strength significantly. Hence, further investigations on these are necessary for more accurate estimation. A fragility analysis was performed to examine the weathering effect on the evaluation of design wind speeds in the AIJ Recommendations. The results indicate the importance of considering the weathering effect.

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