Effects of Support Condition and Dimension of Glass Plates on the Wind Load Resistance

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SUMMARY

The effects of support condition and dimension of glass plate on the wind load resistance are investigated by performing full-scale breakage tests and numerical simulation that can predict glass failure pressures. Full-scale breakage tests were carried out using window specimens whose edges were supported as used in practice, called “elastic support condition”, in order to investigate the application of the existing numerical simulation to such a support condition. The results indicate that the numerical simulation can capture the load resistance obtained from the full-scale breakage tests by adjusting the parameters related to the material properties and testing environment, especially relative humidity. By using the numerical simulation, the examination of the effects of support condition and dimension glass plate, and the comparisons with the Japanese and USA design codes are performed. The results show that the support condition of glass plates affect slightly on the wind load resistance. On the other hand, the load resistance depends on size and aspect ratio more significantly than expected in the Japanese code. Therefore, it is found that the Japanese code seems to overestimate the wind resistance of glass plates because it does not reflect the effects of size and aspect ratio of glass plate, which are considered in the USA code.

key words: Window glass, Elastic support condition, Numerical simulation, Full-scale breakage test, Static fatigue

Finite element analysis

1. INTRODUCTION

Glass failure is caused by static fatigue, which is a time-dependent reduction of strength after the application of certain duration of load. This unique feature should be considered for the evaluation of load resistance of window glasses. Brown’s integral, represented by Equation (1), is known to capture the static fatigue appropriately:

\[ DA = \int_{0}^{\tau_f} [p(t)]^4 \, dt \]  

where \( \tau_f \) is failure time [s]; \( p(t) \) is applied pressure [kPa]; \( s \) is a coefficient (a value ranging from 10 to 26); and \( DA \) is damage accumulation at the critical crack on glass surface. Based on this equation, glass failure occurs when \( DA \) reaches its critical value that depends on glass type, geometry, and the
Due to a large value of $s$, the magnitude of $DA$ becomes too large to deal with easily. Therefore, this figure is usually converted into a form of an equivalent static load, which has been historically used to examine the load resistance\textsuperscript{7-11). The way to convert $DA$ into an equivalent static load, $p_{eq}$, is given by Equation (2):

$$
p_{eq}(t_{ref}) = \left\{ \int_0^T [p(\tau)]^{1/4} \, d\tau \right\}^{1/4} = (DA/t_{ref})^{1/4} \tag{2}
$$

where $t_{ref}$ is reference time [s]; and $T$ is time duration [s] of possible wind loading history, $p(\tau)$, in an assumed design situation. In order to use this equation for calculating the equivalent static load from the time history of general wind loading, $DA$ must be independent of loading pattern. Gavanski\textsuperscript{16} conducted a full-scale breakage test with glass plates simply supported along the edges and showed that Brown’s integral is independent of loading pattern including fluctuating wind pressures. However, glass plates used in actual buildings are not simply supported but elastically supported by gasket along their edges (denoted as “elastic support condition” hereafter). This support condition allows the glass plate to move in the out-of-plane direction at its edge as well as to rotate about the edge. Therefore, the application of Brown’s integral to such a support condition should be examined.

Besides the use of Brown’s integral for the evaluation of load resistance, the relevance of the load resistance used in Japanese window glass design needs to be examined. The load resistance is specified by Notification No. 1458 of the Ministry of Construction\textsuperscript{12} (denoted as “Japanese code” hereafter), which will be denoted as $R_{JAPAN}$ [Pa] for clarity and this takes a form expressed in the following equation:

$$
R_{JAPAN} = \frac{300k_hk_e}{A} \left( \frac{h + \frac{b^2}{4}}{4} \right) \tag{3}
$$

where $k_h$ and $k_e$ are coefficients that depend on glass type and configuration; $A$ is the size of glass plate [m$^2$]; and $h$ is the thickness of glass plate [mm]. This equation is based on the results of an experiment\textsuperscript{19} with glass plate specimens simply supported along the edges. Although this equation has been used for decades, there are a few concerns in the use of this equation. First, the range of size and aspect ratio (AR) of the window glass plates employed in the experiment\textsuperscript{19} is rather limited. Second, the effect of aspect ratio, AR, of window glass plates is not considered in Equation (3). The values of AR for the specimens used in the experiment \textsuperscript{19} are only 1 and 2. Therefore, the effect of AR on glass strength is not clear for a wider range of AR. Third, although the support condition of actual window glass plates varies depending on its design, only one support condition using relatively stiff material was employed in the experiment. Lastly, static fatigue is not directly considered in the evaluation of $R_{JAPAN}$. Although the adequacy of the load resistance evaluated by Equation (3) was investigated from the viewpoint of static fatigue by using the rate of the residual strength of glass plate, based on the theory suggested by Shand\textsuperscript{14} and the experimental results\textsuperscript{15}, the number of specimens used in the experiment was rather limited. Hence, it is not clear whether or not the characteristics of static fatigue are appropriately taken into account in $R_{JAPAN}$.

Contrary to $R_{JAPAN}$ used in Japan, the load resistance employed in the USA design code (ASTM E 1300-16a\textsuperscript{16}) (denoted as “USA code” hereafter) is calculated based on the glass failure prediction model (GFPM) developed by Beason and Morgan\textsuperscript{17,18} which employed theory of static fatigue. Besides the use of theory, there are several differences between the Japanese and USA codes, such as failure probability corresponding to the load resistance, reference time and the consideration of size and AR of window glass plates. Regarding the details of the USA code and its adequacy, refer to Gavanski and Kopp\textsuperscript{19}.

Considering the above-mentioned background, the purpose of the present research is to examine whether or not the load resistance calculated by Equation (3) is appropriate by comparing the results with those directly obtained from Equation (1). As a method for calculating the load resistance of glass plates based on Equation (1), Simiu and Reed\textsuperscript{20,21} proposed a numerical simulation method for predicting the failure pressure of glass plates subjected to fluctuating wind loading. Then, this method was modified by Kawabata\textsuperscript{22} and Gavanski\textsuperscript{16}. This numerical simulation method was verified by comparing the predicted results with those of full-scale breakage tests for glass plates simply supported along the edges\textsuperscript{22}. However, it has not been verified yet for the elastic support condition. Therefore, as the first step of the present study, a full-scale breakage test using glass plates elastically supported along the edges was performed in order to examine...
the application of Brown’s integral to such a support condition, which is the basis of the numerical simulation. After the numerical simulation method has been validated, the evaluation of load resistance of glass plates used in Japan and USA is performed using the results of numerical simulation, focusing on the support condition and dimension of glass plate (size and AR) which is considered only in USA code.

2. FULL SCALE GLASS BREAKAGE TESTS
2.1 EXPERIMENTAL PROCEDURE

In the present study, monolithic annealed window glass plates of 855 mm height, 790 mm width and 3 mm thickness were used, because they are widely used for temporary houses in Japan and easy to handle by one person. The edge of glass plate was fastened with gasket and supported by aluminum frame, similarly in the actual window systems. This specimen is referred as “window specimen” hereafter. Each window specimen was mounted on a pressure box (Fig. 1) connected to “Pressure Loading Actuator (PLA)” (Fig. 2), which was originally developed at the University of Western Ontario (UWO) in Canada, to apply various types of loading to the specimen. This loading device can generate realistic, full-scale, temporally-varying wind pressures\(^{(21)}\). A plywood panel was placed on the front face of the pressure box and its deflection was prevented by inserting wooden pieces behind it. Around the opening in the plywood panel, strips of aluminum plates were fastened with bolts so that they held the window specimen in place at the edges. With this setup, the frame of window were not allowed to rotate nor move in the out-of-plane direction. Hence, it is thought that the rotation and deflection of glass plate with respect to the aluminum frame only affect the failure of specimen.

Fig. 1 Pressure box  
Fig. 2 PLA

Table 1 shows the loading types employed in the test together with the testing environment. In order to reduce the variation of initial strength of glass plate, the specimens produced in the same production line and delivered/preserved in same way were used. Furthermore, close attention was paid to their handling with corporation of a window manufacturing company. Three types of pressure traces were applied to the specimen until it was broken; i.e., two ramp loadings (Ramp 1 and Ramp 2) and realistic dynamic loading (Dynamic). For each loading pattern, 20 specimens were tested. Moreover, in order to examine the effect of humidity, an additional experiment was carried out, denoted as added_Ramp 2, under the testing condition where humidity was as low as that when Dynamic test had been performed. The reason for this additional test will be explained later. Because of the limited numbers glass plates left which were manufactured in the same production line as the others used for the test, added_Ramp 2 was performed with only 5 specimens.

Table 1 Loading types and testing environment

| Loading rate  | Ramp 1 | Ramp 2 | Dynamic | added_Ramp 2 |
|---------------|--------|--------|---------|--------------|
| Number of specimens | 20     | 20     | 20      | 5            |
| Room temperature [°C] | 19-22  | 19-23  | 11-28   | 20-25        |
| Relative humidity(RH) [%] | 38-55  | 42-66  | 4-22    | 12-18        |

Dynamic loading (Dynamic) was produced by using the time history of wind pressure coefficient obtained from a wind tunnel test with a model of a low-rise residential building (\(B \times D \times H = 9\) m\(\times10\) m\(\times8\) m\(^2\)). Area-averaged wind pressure coefficients, \(C_{pw}\), whose tributary area was the same as that for the window specimen and which were calculated using the tributary area method employed in Gavanski and Uematsu\(^{(20)}\), were obtained for all the possible locations on the walls and wind directions. Among them, time history of \(C_{pw}\) that gave the minimum peak value was selected. The time history of wind pressure, \(p(t)\), is given by the following equation:

\[
p(t) = 0.5 \rho V_f^2 C_{pw}(t)
\]

where \(V_f\) is reference wind speed [m/s]; and \(\rho\) is air density [kg/m\(^3\)]. The value of \(V_f\) is assumed 50 m/s as an initial value, which roughly corresponds to the maximum wind speed specified in the AJI Recommendations for Loads on Buildings\(^{(20)}\). If the specimen does not break at the end of the application of the pressure trace, it is desirable to keep applying the same pressure trace repeatedly until the specimen is broken.
as was done in Gavanski. However, we decided to recalculate the input pressure trace with increased \( V_t \) by 3 m/s and to apply the pressure trace to the same specimen in order to make the testing time shorter. The purpose of the present tests was to examine whether or not the loading pattern affects the glass failure that is evaluated with \( DA \) only. Hence, the change of time scale with an increase in \( V_t \), which is the results of the present load application method, will not affect the result. The pressure time history for each scaling wind speed was applied sequentially with no pause. Fig. 3 shows an example of entire pressure time history applied to the specimen. Points at which \( V_t \) changes are indicated by a change in color.

![Figure 3: Pressure time history of “Dynamic” used in the tests](image)

2.2 TEST RESULTS

Table 2 summarises the test results for all loading patterns. Failure pressure, \( p_f \), represents a pressure applied at the moment of glass failure, as measured by a pressure transducer attached to the pressure box. Simple mean, Mean, maximum, Max, minimum, min, standard deviation, S.D, and coefficient of variation, COV, of failure pressures for the all specimens are shown in the table.

| \( p_f \) | Ramp 1 | Ramp 2 | Dynamic | added | Ramp 2 |
|---------|--------|--------|---------|-------|--------|
| Mean [kPa] | 7.48 | 8.66 | n/a | 9.85 |
| Max [kPa] | 8.74 | 10.38 | n/a | 10.68 |
| min [kPa] | 5.78 | 6.71 | n/a | 8.75 |
| S.D [kPa] | 0.92 | 0.89 | n/a | 0.7 |
| COV [-] | 0.12 | 0.10 | n/a | 0.07 |

| \( p_{eq,6} \) | Ramp 1 | Ramp 2 | Dynamic | added | Ramp 2 |
|---------|--------|--------|---------|-------|--------|
| Mean [kPa] | 8.11 | 8.13 | 9.48 | 9.27 |
| Max [kPa] | 9.85 | 9.59 | 10.93 | 10.15 |
| min [kPa] | 6.19 | 6.17 | 6.57 | 8.21 |
| S.D [kPa] | 0.89 | 1.07 | 1.09 | 0.71 |
| COV [-] | 0.11 | 0.13 | 0.12 | 0.07 |

The value of \( p_f \) for faster loading (Ramp 2) is generally larger than that for slower loading (Ramp 1), which is consistent with the expectation from Equation (1).

With respect to dynamic loading (Dynamic), the results cannot be evaluated by failure pressure defined above, because the same pressure level can occur at different time steps; that is, the failure pressure itself does not represent the amount of damage accumulation. Hence, equivalent static load, \( p_{eq} \), given by Equation (2), is used for comparing the results for various loading patterns. As for the reference time, \( t_{ref} \), which should be the same value in all loading patterns, 6 s was employed because it corresponds to the value assumed in the Japanese code according to Miura. The value of coefficient \( s \) was assumed 17 based on the results for the two ramp loadings. The calculated values of \( p_{eq,6} \) are also included in Table 2.

It is widely accepted that the typical COV value of glass strength is approximately 0.22. Assuming that it can be compared with COV values of equivalent load in present test, they are relatively small (0.11 - 0.13), indicating less variability in failure pressure.

From these results, \( p_{eq,6} \) for Dynamic seems to be larger than those for ramp loadings. The reason for this difference is likely to be the effect of relative humidity, RH. As shown in Table 1, RH during the ramp loading tests was much higher than that during the Dynamic test. Note that the ramp loading tests were performed first and the Dynamic test was performed two months later, which was in December when air conditioning was on to keep the room warm. Wiederhorn mentioned that the strength of glass plates decreases as RH increases, because water promotes the growth of crack on the glass surface. Consequently, glass plate failure seems to have been delayed in the Dynamic test because of the low RH, resulting in larger \( p_{eq,6} \). In order to examine the above-mentioned hypothesis, we have performed a further test (added_Ramp 2) in the condition of RH almost the same as that one in Dynamic test. The \( p_{eq,6} \) values for added_Ramp 2 is larger than those for the other ramp loading tests as shown in Table 2, and similar to that from Dynamic test. Hence, the difference in \( p_{eq,6} \) between the Dynamic and ramp loadings seems to have been caused by the difference in humidity. Since the number of specimens used in added_Ramp 2 test was still small considering the large variance of glass strength, the presented results may not be sufficient enough to validate Brown’s integral. However, based on the current results, we can conclude that Brown’s integral can be applied to dynamic loading as well as to ramp loading when the glass edges are elastically supported, if the effect of humidity on the glass
strength is considered appropriately.

In the following chapter, numerical simulation will be performed to investigate whether or not the testing environment, especially RH, affects the load resistance by adjusting the parameters of material characteristics.

3. NUMERICAL SIMULATION

There is a numerical simulation method for predicting failure pressure of glass plates subjected to wind loading, originally proposed by Simiu and Reed\textsuperscript{20,21} and modified by Kawabata\textsuperscript{9} and Gavanski\textsuperscript{8}. All the previous numerical simulations were performed under the condition where glass plates were simply-supported along the edges. In the present study, on the other hand, we attempt to modify this numerical simulation method so that we can apply it to the glass plates whose edges are elastically supported.

3.1 METHODOLOGY OF SIMULATION

The methodology of the numerical simulation is briefly explained here (regarding the detail, see Gavanski\textsuperscript{8}). The following equation describes the time-dependent glass strength, $S(M_j, a_0, t)$, of an element on a glass plate at location $M_j$, which contains a crack oriented normal to the direction $a_0$ after a time duration $t$ [s] of load application:

$$
S(M_j, a_0, t) = \left( S_a(M_j, a_0) \frac{K_{IC}}{K_n} \right)^{\alpha - 2} - \frac{n - 2}{2} A' Y^2 K_n^{-2} \int_0^t \sigma' \left( M_j, a_0, \tau \right) d\tau
$$

(5)

where $S_a(M_j, a_0)$ is the initial strength of the element at point $M_j$ that contains a crack oriented normal to the direction $a_0$ after a load is applied for $t$ [s]. $K_n$, $K_a$, and $Y$ are fracture toughness, initial stress intensity factor, and geometrical shape factor, respectively, which represent the characteristics of the material; $A'$ and $n$ are crack growth coefficients depending on the temperature and RH of the air surrounding the window specimens. The value of $S_a(M_j, a_0)$ is generated by using the Monte-Carlo technique assuming that $S_a(M_j, a_0)$ follows the Weibull distribution:

$$
P(S_a, A, a_i < a < a_j) = 1 - \exp \left( - \frac{S_a(M_j, a_i)}{S_a(A, a_i < a < a_j)} \right)^n
$$

(6)

where $P(S_a, A, a_i < a < a_j)$ is the probability of the initial strength of an element of size $A$, which contains a crack with an orientation angle of $a_i < a < a_j$; $S_a(A, a_i < a < a_j)$ is a scale parameter; and $m$ is the shape parameter. $S_a(A, a_i < a < a_j)$ and $m$ were obtained from a ring-on-ring tests which can apply uniform stress by means of a loading ring in both circular and radial directions on a small size specimen placed on a supporting ring. With this test, the specimen edge conditions do not affect the failure stress.

$$
\sigma(M_j, a_0, t) = \sigma_a(M_j, t) \cos^2 \alpha_i + \sigma_n(M_j, t) \sin^2 \alpha_i + 2 \tau_n(M_j, t) \sin \alpha_i \cos \alpha_i
$$

(7)

where $\sigma_a(M_j, t)$ and $\sigma_n(M_j, t)$ are normal stresses and $\tau_n(M_j, t)$ is shear stress at each element location $M_j$ on the glass surface. They are computed by Finite Element Method (FEM), using a commercial software ABAQUS 6.13.4. These values depend on the support conditions at the edges.

By comparing the strength $S(M_j, a_0, t)$ with the stress $\sigma(M_j, a_0, t)$ at each location $M_j$, direction $a_0$, and time $t$, the failure is defined as the moment when the following relationship is achieved:

$$
\sigma(M_j, a_0, t) > S(M_j, a_0, t)
$$

(8)

The earliest failure time for all locations and directions is defined as a failure time, $t_f$ of the glass plate. The simulation was repeated 10,000 times for each condition.

3.2 INPUT PARAMETERS FOR SIMULATION

In the present numerical simulation, a monolithic annealed glass plate of 855 mm height × 790 mm width × 3 mm thickness, which is the same as those used for the full-scale breakage tests, is employed. The entire glass plate is divided into 225 elements ($M = M_1 - M_{225}$) and each element contains cracks having 10 different directions with increments of $\pi / 10$ ($a_0 = a_0 - a_0$). The loading patterns are the two ramp loadings used in the full-scale breakage tests. The parameters in the simulation model are adjusted so that they represent the testing environment. These values are shown in Table 3 and described as follows:
Table 3 Parameters set in the numerical simulation for reproducing full-scale breakage tests

| Parameter | Ramp 1 | Ramp 2 | Dynamic |
|-----------|--------|--------|---------|
| $S_0 \text{ (1 m$^2$)}$ | 67.7 | 67.7 | |
| $m$ | 10.58 | 10.58 | |
| $K_{ic}$ | 0.75 | 0.75 | |
| $K_a$ | 0.55 | 0.55 | |
| $Y$ | 1.12 | 1.12 | |
| $A'$ | 1.08 | 0.108 | |
| $n$ | 19.69 | 19.69 | |
| RH | 50 % | 10 % | |

(1) $Y$, $K_{ic}$, $K_a$

$Y = 1.12$ is selected as a value corresponding to a long single-ended crack in a semi-infinite solid. $K_{ic} = 0.75$ is used, which corresponds to that for soda-lime silicate glass. The value of $K_a$ under usual condition ranges from 0.25 to 0.75 for soda-lime silicate glass. The value of 0.25 corresponds to the static fatigue where cracks grow slowly, while the value of 0.75 corresponds to $K_{ic}$ which indicates that the rapid crack growth process begins immediately. In the present study, $K_a$ is assumed to be 0.55 as an average value.

(2) $S_0$, $m$

$S_0 \text{ (1 m$^2$)} = 67.7 \text{ MPa}$ and $m = 4.88$ were obtained from a ring-on-ring test, where all the specimens were cut out from the same glass plates used for the full scale brakeage tests. The scale parameter, $S_0$, affects the magnitude of failure pressure of glass plates. The shape parameter, $m$, affects the variation of failure pressures. When the results from the full-scale brakeage tests were directly compared with those from the numerical simulations with these $S_0$ and $m$ values, a relatively large discrepancy was observed. The value of $m$ obtained from the ring-on-ring test was 4.88, while that obtained from the full-scale brakeage test was 10.58. This difference may have caused the discrepancy in the results between numerical simulation and full-scale breakage test. The small number of $m$ obtained from the ring-on-ring test, which means large variation in the initial strength, may be because the number of specimen was not large enough for the determination of stable $m$ value (25 samples were used for the ring-on-ring test). Therefore, in order to reproduce the results of full-scale brakeage test appropriately, the shape parameter $m$ for the initial glass strength used in the numerical simulation is assumed to be the same as that obtained from the full-scale brakeage test; that is $m = 10.58$.

(3) $A'$, $n$

Crack growth factors, $A'$ and $n$, are known to depend on the environment such as RH and temperature where glass is in use. The strength of glass plate decreases as RH increases as mentioned in Section 2.2. In the previous study, $n = 19.69$ and $A' = 1.08$, which correspond to the temperature of $20 \text{ °C}$ and the RH of 50 %, were employed; this condition is similar to the environment when the two ramp loading tests were performed. Hence, these parameters were employed for reproducing the ramp loading test results in the numerical simulation. As for the dynamic loading test where RH was approximately 10 %, the same values of $A'$ and $n$ as ramp loadings cannot be used. Wiederhorn showed the relationship between crack growth speed and RH (described as Figure 1 of Wiederhorn). Furthermore, crack growth speed, $v$, can be given by Equation (9), as a function of $A'$, $n$ and stress intensity factor, $K_i$.

$$v = A' K_i^n$$  \(\text{(9)}\)

According to the previous study, $n$ does not depend on RH but it does on temperature. Hence, the present study assumes that the parameter $A'$ is the one representing the effect of RH. The values of $A'$ for a specific RH can be determined based on Figure 1 of Wiederhorn and Equation (9) with constant $K_i$ and $n$, and was calculated as $A' = 0.108$ for RH of 10 %.

3.3 COMPARISON WITH THE RESULTS OF FULL-SCALE BREAKAGE TESTS

Fig. 4 shows comparisons between full-scale brakeage tests and numerical simulation for different RH values in terms of failure probability and the equivalent load, $p_{eq}$. Note that $p_{eq}$ was calculated from the applied pressure time series until the glass plate failure by using Equation (2) with the reference time of $t_{ref} = 6 \text{ s}$. The results for Ramp 1 and Ramp 2 are combined in Fig.4 because these tests were conducted in the same relative humidity environment, and the results are independent of loading speed, as mentioned above.

It is clear that the numerical simulation captures the test results fairly well for both RH values, which indicates that the present numerical simulation can be used for the calculation of the load resistance of window glass plates whose edges are elastically supported by adjusting the parameters of material characteristics and testing environments, especially RH.
4. DISCUSSION

4.1 COMPARISON WITH JAPANESE DESIGN CODE

In this section, the load resistance, $R$, evaluated by the Japanese code, defined as Equation (3), is investigated by using the numerical simulation results.

Based on Miura\textsuperscript{15}, $R\text{JAPAN}$ described as Equation (3) can be recognized as an equivalent static load with an evaluation time, $t_{65}$, of 6 s, at a failure probability of 1/1000. Hence, in order to compare the simulation results with $R\text{JAPAN}$ obtained from the Japanese code, failure pressure corresponding to a failure probability of 1/1000 was obtained from the results of numerical simulation where static load is applied for the duration of 6 s to glass specimens.

The glass type and thickness under consideration here are soda-lime glass and 3 mm, respectively. In order to investigate the effects of glass size and aspect ratio (AR), the size and AR of glass plate are varied from 0.25 m\(^2\) to 2.25 m\(^2\) and from 1 to 3, respectively.

(1) Input parameters for numerical simulation

In order to compare $R$ obtained from the numerical simulation with those from the code provisions, present study assumes the input parameters as shown in Table 4, considering the practical conditions during wind storms as well as those providing conservative results for $R$. The details of each parameter are as follows.

Initial strength $S_0$, fracture toughness $K_{IC}$, and geometrical shape factor $Y$ are specific values for soda-lime glass. Hence, they are the same as those in Table 3. The shape parameter $m$ of Weibull distribution for initial strength affects the variation of failure pressure. According to the previous studies\textsuperscript{5(6)}, $m = 6$ is selected as a representative value.

Crack growth factors, $A'$ and $n$, strongly depend on the relative humidity, RH, as mentioned above. Considering the windstorm condition such as typhoons, we assume that RH is 100 %, resulting in a conservative estimation of $R$. In this case, $A'$ is equal to 10.8.

An initial stress intensity factor, $K_0$, is assumed to be equal to $K_{IC}$, so that the simulation provides the results on the safer side\textsuperscript{20,21}.

Table 4 Parameters set in numerical simulation in order to compare with $R$ from Japanese design code

| $S_0$(MPa) | $m$ | $K_0$ (MPa $\cdot$ m\(^{1/2}\)) | $K_{IC}$ (MPa $\cdot$ m\(^{1/2}\)) | $Y$ | $A'$ (MPa$^n$ m\(^{3/2}/A$) | $n$ | RH [%] |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 67.7 | 6 | 0.75 | 0.75 | 1.12 | 10.8 | 19.69 | 100 |

(2) Results

1) Effect of support condition

Prior to the examination of $R$ obtained from the Japanese code, the effect of support condition on $R$ was investigated by comparing the results for elastically supported condition and those for simple support condition. The former is more practical but requires more complicated computations of stresses induced in the glass plate used for Equation (7). The latter is generally used in practical design of glass windows, because it requires less computation time. Fig. 5 shows the variation of $R$ with glass size for different aspect ratios, AR. In the figure, the results for simple support and elastic support are plotted. It is clear that the results for these two support conditions agree well with each other for all glass size and AR values tested. This means that the effect of the support conditions of glass plates on $R$ is very small compared to the other parameters when simply support and elastically support conditions are considered. Therefore, the results for simple support condition are used for further examination of $R$ because it is easier and requires less computational time to perform the FEM analysis.

![Fig. 5 Effect of support condition on R](image-url)
2) Effect of glass plate size

Fig. 6 shows comparisons of the load resistance, \( R \), calculated from the numerical simulation and those by using Equation (3) for various glass size and aspect ratio (AR) values. The values calculated from the code are inversely proportional to the size of glass plate as described by Equation (3). The simulation results follow this trend that the \( R \) values become larger as the size of glass plate, \( A \), become smaller. However, the difference between the simulation results and code values increases as the size of glass plate decreases. The largest difference is as large as 49 % when \( AR = 2 \) and \( A = 0.25 \) m\(^2\).

In the experiment\(^{19}\), which was the basis of the Japanese code, the range of glass size of specimen was from 0.75 m\(^2\) to 3 m\(^2\). Hence, the \( R \) of small size glass plate such as smaller than 0.5 m\(^2\) might not be calculated correctly by Equation (3).

3) Effect of aspect ratio (AR) of glass plate

Fig. 7 shows comparisons of \( R \) calculated from the numerical simulation and those by using Equation (3) for various glass size and AR values. The simulation results generally decreases with an increase in AR except for \( A = 0.25 \) m\(^2\), while the code value provided by Equation (3) is independent of AR. The reason why AR of glass specimen affects \( R \) is further discussed in Section 4.3.

4.2 COMPARISON WITH USA CODE

In addition to the examination of the Japanese code, a similar comparison was performed using the current window glass design codes in the USA (ASTM E 1300-16\(^{16}\)).

(1) Input parameters for numerical simulation

The values of the parameters involved in the simulation are the same as those used in the previous section. However, in the USA code, \( R \) is specified as 3 s equivalent static load at a failure probability of 8/1000 for glass plates simply supported along the edges. Hence, failure pressure corresponding to a failure probability of 8/1000 was obtained from the results of numerical simulation where static load was applied for the duration of 3 s to glass specimens.

(2) Results

Figs. 8 and 9 show comparisons for \( R \) between simulation and the USA code, which correspond to Fig. 6 and 7 when the numerical simulation result are compared with the Japanese code, respectively. The agreement between these two results is fairly good. This means that the USA code appropriately takes into account both the effect of glass plate size and aspect ratio.
4.3 EFFECT OF ASPECT RATIO (AR)

It is found that the load resistance, $R$, depends on the shape of glass plate such as aspect ratio (AR). In order to investigate the mechanism of this behavior, we focused on the distribution of stress induced in the glass plate.

Fig. 10 shows the stress distribution in the glass plates with AR = 1 - 3, $A = 1 \text{ m}^2$ and $h = 3 \text{ mm}$ when the uniform pressure of 1.5 kPa is applied. These are obtained from the FEM analysis. It is noted that each figure shows only one quarter area of the whole plate considering the symmetry; the center of the glass plates is located at the left lower corner of the figure.

In all cases, large stresses occur near the corner. The values of these large stresses decrease as AR increases. On the other hand, the magnitude of stress near the center increase as AR increases, and the area of larger stresses expands with increasing AR. It is thought that such a difference in stress distribution caused by AR affects the failure pressure.

Although the maximum stress when AR = 1 is larger than those in the other AR cases, $R$ for AR = 1 shown in Fig. 7(c) is larger than or equal to these in the other cases. This indicates that $R$ does not depend only on the largest magnitude of stress.

Considering the fact that glass plate failure is determined by the simple relationship between $S (M, \alpha, \tau)$ and $\sigma (M, \alpha, \tau)$ and cracks exist randomly on the surface of the glass plate, i.e., $S (M, \alpha, \tau)$ in Equation (8) varies with the locations on glass plate, it is expected that the area of relatively large stresses in the glass plate affects the glass plate failure significantly. If this is the case, glass plate failure origin should not necessarily occur in the area where very large stresses are induced. In order to confirm this presumption, the ratio of “failure origin point” obtained from the numerical simulation is plotted in Fig. 11. The “failure origin point” refers to as the location that achieves the relationship described by Equation (8) first among all the locations on a glass plate under consideration. The size of circle represents the percentage of failure origin. Comparing Fig. 11 with Fig. 10, it is found that the locations of failure origins are surely concentrated in the area where large stresses occur such as in the case of AR = 1 but this is not always the case and the area of the possible failure origin location increases as AR increases. Based on this examination, it seems that our presumption seems to be appropriate and, therefore $R$ depends on AR that affects the stress distribution of glass plate.
found that the relative humidity affects the failure pressures significantly.

By comparing the results obtained from the full-scale breakage tests with those from the numerical simulation, the applicability of numerical simulation for the elastic support condition was examined. The results indicate that the numerical simulation can capture the full-scale breakage test results by adjusting parameters of material characteristics and considering testing environment, especially the relative humidity. Therefore, the present numerical simulation can be used for the calculation of the load resistance of window glass plates which are elastically supported at the edges. Moreover, the results for both simply supported and elastically supported glass plates agree relatively well with each other for all the glass size and aspect ratios tested in the present paper. This means that the effect of support condition on the load resistance is found to be insignificant for simply supported and elastically supported conditions.

With the numerical simulation modified for the elastic support condition, comparisons of the values of load resistance obtained from the Japanese and USA codes and those from the numerical simulation were performed. The results indicate that the load resistance provided by the Japanese code seems to overestimate the wind-resistance of glass plates. The USA code, on the other hand, considers the effect of glass plate size and aspect ratio on the load resistance appropriately, indicating that it gives more reasonable values of the load resistance than the Japanese code. It is found that the effect of aspect ratio on failure pressure is caused by difference in the stress distribution.

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REFERENCES

1) Minor, J. E., “Window glass design practices”, A review, J. Struct. Div., 107(ST1), 1-12, (1981)
2) Brown, W. G., “A load duration theory for glass design”, Pub. No. NRC 12354, National Research Council of Canada, Ottawa, (1972)
3) Brown, W. G., “A practicable formulation for the strength of glass and its special application to large plates”, Pub. No. NRC 14372, National Research Council Canada, Ottawa, (1974)
4) Dalgliesh, W. A., “Assessment of wind loads for glazing design”, Symp. on Practical Experiences with Flow-Induced Vibrations, Karlsruhe, Germany, 696-708, (1979)
5) Kawabata, S., “Study on wind resistance design of glass plate for cladding”, Ph.D. Thesis, Nippon Sheet Glass Co. Ltd., Japan (in Japanese), (1996)
6) Gavanski, E., “Behavior of glass plates under wind loads, Ph.D. Thesis”, The University of Western Ontario, London, Ontario, Canada, (2009)
7) Holmes, J. D., “Wind action on glass and Brown’s integral”, Eng. Struct., 7 (4), 226-230, (1985)
8) Kanabolo, D. C., Norville, H. S., “The strength of new window glass plates using surface characteristics”, Glass Res. and Testing Lab., Texas Tech. University, Lubbock, Tex., (1985)
9) Reed, D. A., “Influence of non-Gaussian local pressures on cladding glass”, J. Wind. Eng. Ind. Aerodyn., 48(1), 51-61, (1993)
10) Li, Q. S., Calderone, I. J., Melbourne, W. H., “Probabilistic characteristics of pressure fluctuations in separated and reattaching flows for various free-stream turbulence”, J. Wind. Eng. Ind. Aerodyn., 82, 125-145, (1999)
11) Ko, N. H., You, K. P., Kim, Y. M., “The effect of non-Gaussian local wind pressures on a side face of a square building”, J. Wind. Eng. Ind. Aerodyn., 93, 383-397, (2005)
12) MLIT, “Notification No. 1458 of the Ministry of Construction”, (2000)
13) Miyoshi, S., “Wind pressure test on glass plate”, Summaries of technical paper of annual meeting 100, Architectural Institute of Japan, 13-18, (1964)
14) Shand, E. B., “Experimental study of Fracture of Glass: II, Experimental Data”, J. Am. Ceram. Soc., 37(12), 559-572, (1954)
15) Miura, T., Kasagi, S., Miyoshi, S., “Study on Wind-resistance of glass panels (Part3) Fatigue effect on wind-resistance of glass panels”, Reports Res. Lab. Asahi Glass Co., Ltd., 24(2), 151-157, (1974)
16) ASTM, “Standard practice for determining load resistance of glass in buildings”, ASTM E 1300-16a, West Conshohocken, Pa., (2016)
17) Beason, W. L., “A failure prediction model for window glass”, Ph.D. Thesis, Texas Tech. University, Lubbock, Texas, (1980)
18) Beason, W. L., Morgan, J. R., “Glass failure prediction model.” Journal of Structural Engineering, 110(2), 197-212, (1984)
19) Gavanski, E., Kopp, G. A., “Storm and gust duration effects on design wind loads for glass.” Journal of Structural Engineering, 137(12), 1603-1610, (2011)
20) Reed, D. A., Simiu, E., “Wind Loading and strength of cladding glass”, J. Struct. Eng., 110 (4), 715-729, (1984)
21) Simiu, E., Reed, D. A., “Probabilistic design of cladding glass subjected to wind loads”, 4th Int. Conference on Applications of Statistics and Probability in Soil and Structural Engineering, Universita di Firenze, Italy, (1983)
22) Kopp, G. A., Morrison, M. J., Gavanski, E., Henderson, D. J., Hong, H. P., ““Three little pigs” project: hurricane risk mitigation by integrated wind tunnel and full-scale laboratory tests”, Nat. Haz. Rev., 11(4), 151-161, (2010)
23) Gavanski, E., Uematsu, Y., “Local wind pressures acting on walls of low-rise buildings and comparisons to the Japanese and US wind loading provisions.” Journal of Wind Engineering and Industrial Aerodynamics, 132, 77-91, (2014)
24) Architectural Institute of Japan, “Recommendations for Loads on Buildings (2015 edition)”, (2015)
25) Wiederhorn, S. M., “Influence of water vapor on crack propagation in soda-lime glass”, J. Am. Ceram. Soc., 50 (8), 407-414, (1967)
26) Wiederhorn, S. M., Freiman, S. W., Fuller Jr, E. R., Simmons, C. J., “Effects of water and other dielectrics on crack growth”, J. Mat. Sci., 17(12), 3460-3478, (1982)
27) Tang, Z., Brow, R. K., “Environmental Fatigue of Silicate Glasses in Humid Conditions”, Int. J. Appl. Glass Sci., 5(3), 287-296, (2014)