Basis for ASTM E 1300 Annealed Glass Thickness Selection Charts

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Abstract: In the early 1980s, a glass failure prediction model (GFPM) was introduced to resolve differences in U.S. industry procedures used to determine the minimum thickness of glass required to resist a specified uniform lateral pressure. The differences in these industry procedures continue to cause problems for designers who are forced to choose between two different glass thickness selection methods that result in different specified thicknesses of glass for the same loading. Since its introduction, the GFPM has helped resolve industry conflicts as it has gained increasing acceptance. In the late 1980s, the GFPM was used to develop glass thickness selection information that is incorporated in ASTM E 1300-94. The purpose of this paper is to provide documentation for the ASTM E 1300-94 glass thickness selection procedure and to propose improvements. The proposed improvements include modifications to the optional procedure for calculating the probability of failure of a rectangular glass plate, and the presentation of a new set of dual-unit glass thickness selection charts.

INTRODUCTION

Glass breakage in severe windstorms is usually the result of a combination of lateral pressures and windborne missile impacts. Research has shown that all types of monolithic glass, including annealed, heat-strengthened, and tempered glass, are susceptible to breakage as the result of missile impact; and that thicker glass is not necessarily more resistant to the impact of windborne missiles than thinner glass (Minor et al. 1978). Whether or not a particular window will be subjected to the effects of windborne missiles depends upon the characteristics of the built environment in the surrounding area. If window glass is located in an area where inadequate attention has been paid to the design and construction of surrounding structures, the failure of window glass tends to be dominated by the impact of windborne missiles (Minor et al. 1978; Beason et al. 1984). The only practical solutions to controlling the failure of window glass that is subjected windborne missile impact involve improved design and construction of surrounding structures, the use of shutters to prevent the impact of windborne missiles, or the use of window film or laminated glass. A complete discussion of the performance of window glass subjected to missile impact is beyond the scope of this paper. Rather, this paper is focused on a treatment of the design of window glass to resist uniform lateral pressures.

All window glass can be subject to the effects of lateral pressures; hence, all window glass must be designed to withstand the lateral pressure effects of severe windstorms. If all other factors such as the area of the glass and the glass type are held constant, the resistance of window glass to uniform lateral pressures is directly related to the thickness of the glass. Therefore, procedures that are used to determine the proper glass thickness for a particular situation are frequently referred to as glass thickness selection procedures. Glass thickness selection procedures are generally based either on theoretical formulations that attempt to model the performance of glass from an engineering mechanics basis, or on empirical representations of large amounts of glass failure strength data.

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During the 1960s and early 1970s, glass thickness selection was accomplished using a single chart, which presents the variation of the glass design load as a function of glass thickness and area. This glass thickness selection chart is referred to herein as the traditional glass thickness selection chart. It is based on empirical representations of the results of strength tests conducted on freshly manufactured glass specimens (Orr 1957; Hershey and Higgins 1973). As a result of widespread industry support in the 1970s and 1980s ("Glass" 1975; "Strength" 1980), the traditional glass thickness selection chart continues to be incorporated into model building codes throughout the United States today (*Standard building code* 1994; *Uniform building code* 1993; *BOCA* 1994).

In the late 1970s, a new set of glass thickness selection charts were introduced by PPG Industries Inc. (*PPG* 1979). The PPG glass thickness selection charts were developed using a maximum tensile stress failure theory combined with results from a geometrically nonlinear finite-element stress analysis (Tsai and Stewart 1976; Krall et al. 1981). In this procedure, a maximum allowable design tensile stress was established based on a statistical treatment of a large quantity of failure stress data. In addition, the maximum allowable design tensile stress was lowered to reflect the degradation of glass strength as the result of in-service exposure (Tsai and Stewart 1976; Krall et al. 1981). These data were then used to construct a group of glass thickness selection charts for use in routine glass design. An individual glass thickness selection chart was developed for each thickness and type of glass considered. The PPG glass thickness selection procedure allows the proper thickness of glass to be determined as a function of area, thickness, and aspect ratio (long dimension divided by short dimension) (*PPG* 1979).

While the introduction of the PPG glass thickness selection charts was clearly a step forward from a technical standpoint, there has been resistance to the incorporation of the PPG glass thickness selection charts into building codes and standards. Perhaps this resistance is the result of the increased complexity associated with the use of multiple glass thickness selection charts. However, the most probable cause involves controversies surrounding the differences in glass thickness recommendations arrived at through the use of the two different procedures. Comparisons of annealed glass thickness recommendations arrived at through the use of the PPG and the traditional procedures show that in most practical applications the PPG procedure results in the specification of thicker glass (Beason and Norville 1989). One reason for this difference is that the traditional glass thickness selection chart reflects the strength of freshly manufactured glass, while the PPG glass thickness selection charts reflect a strength reduction factor to account for well-documented in-service strength reductions (Beason 1980;

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Abiassi 1981; Norville and Minor 1985). This situation created a significant controversy between the two different groups of proponents for the traditional and PPG glass thickness selection procedures. Glass designers were left with no universally acceptable glass thickness selection procedure.

Beason (1980) introduced a glass failure prediction model (GFPM). The GFPM is a theoretical procedure that allows the probability of failure of a glass plate to be calculated in terms of the glass plate geometry, load duration, elastic properties of glass, the surface condition of the glass, and the magnitude of the applied load. As such, the GFPM accounts for a wide range of variables that are known to affect the strength of glass. Insofar as the theory incorporated in the GFPM has been shown to accurately represent the variation of glass strength, the GFPM is an improvement over both the traditional and the PPG glass thickness selection procedures. Therefore, the GFPM was offered as a compromise to resolve the controversy introduced by the differences in the traditional and PPG glass thickness selection charts (Beason and Morgan 1984).

The GFPM was used as the basis for the development of a set of annealed glass thickness selection charts that were incorporated in ASTM E 1300-89 ("Standard practice" 1989). The glass thickness selection charts incorporated in ASTM E 1300-89 provide a useful compromise for the design of annealed glass. However, ASTM E 1300-89 could not be used for general glass design because it did not allow for the treatment of different types of glass such as heat-treated, insulating, and laminated glass. This problem was addressed with the introduction of revisions incorporated into ASTM E 1300-94 ("Standard practice" 1994). The ASTM E 1300-94 procedure allows the treatment of other types of glass using a set of glass strength factors and the annealed glass thickness selection charts that were originally incorporated in ASTM E 1300-89.

ASTM E 1300-94 presents two different methods for selecting the proper thickness of annealed glass required to resist a specified 60-s duration uniform lateral pressure. The first method involves the use of glass thickness selection charts. One set of glass thickness charts is presented for SI units and one set of glass thickness selection charts is presented for U.S. customary units. Both sets of charts present the relationship between the glass plate geometry and the 60-s duration uniform lateral pressure corresponding to a probability of failure of 0.008. These parameters were selected to provide continuity with the traditional and PPG glass thickness selection charts discussed previously. In addition, ASTM E 1300-94 presents a nonmandatory procedure that can be used to calculate the probability of failure, other than 0.008, associated with a glass plate subjected to a 60-s duration uniform lateral pressure. The purpose of this paper is to present the basis for the GFPM glass thickness selection procedures incorporated in ASTM E 1300-94 and to recommend improvements.

The remainder of this paper is divided into three major sections. The next section presents a review of the formulation of the GFPM and an improved procedure that can be used to extend the capabilities of the ASTM E 1300-94 optional procedure for estimating the probability of failure of rectangular glass plates. The proposed improvements allow for larger lateral pressures and different load durations. This is followed by a section that introduces a new set of dual-unit glass thickness selection charts. The new set of charts allows the number of glass thickness selection charts incorporated in ASTM 1300-94 to be cut in half. The final section presents conclusions and recommendations.

FAILURE PREDICTION MODEL

The glass failure prediction model is a theoretical formulation that allows the probability of failure of a laterally loaded glass plate to be calculated in terms of two parameters, m and k, which represent the severity and distribution of surface flaws (Beason 1980; Beason and Morgan 1984). The glass failure prediction model incorporates the effects of all factors that are known to influence the strength of glass such as load duration, plate geometry, and glass surface condition. The initial portion of this section presents a review of the formulation of the GFPM and the latter portion discusses the use of the GFPM.

Formulation of GFPM

Failure strength data associated with glass plates involve a great deal of variability. Coefficients of variation as high as 25% are common with annealed glass strength data. This is the case because the strength of glass is controlled by the random characteristics of surface flaws, which act in combination with nominal tensile stresses to cause large local stress concentrations.

The GFPM is based upon a statistical theory of failure for brittle materials advanced by Weibull (1939). The Weibull theory incorporates the effects of both nominal stresses and surface flaw characteristics. This failure theory states that the probability of failure, P_f, of a brittle material can be represented as follows:

$$P_f = 1 - e^{-B} \tag{1}$$

where B reflects the risk of failure as a function of the surface flaw characteristics and the nominal stress distribution.

In the case of glass, the magnitude of the risk function, B, depends upon the distribution of tensile stress across the surface of the glass, and the distribution and severity of surface flaws (Beason 1980). Beason and Morgan (1984) introduced the following expression for the risk function, B, that is applicable for rectangular glass plates exposed to uniform lateral loads of constant duration:

$$B = \frac{k}{(ab)^{m-1}} (Eh^2)^m \left(\frac{t_d}{60}\right)^{m/16} R\left(m, \hat{q}, \frac{a}{b}\right) \tag{2}$$

where a and b are the rectangular dimensions of the plate ($a > b$); h = true thickness of the glass plate; m and k are the glass surface flaw parameters; t_d = load duration expressed in seconds; E = modulus of elasticity, which is taken to be 71.7 $\times 10^6$ kPa (10.4 $\times 10^6$ psi) for glass (ASTM E 1300-94); and $R(m, \hat{q}, a/b)$ = risk factor.

The risk factor, $R(m, \hat{q}, a/b)$, is a nondimensional function (Beason and Morgan 1984) whose magnitude depends upon the value of the m surface flaw parameter selected and the distribution of nondimensional tensile stresses across the surface of the glass. The distribution of nondimensional tensile stresses across the surface of the glass depends upon the aspect ratio, a/b (long dimension divided by short dimension), and the magnitude of the nondimensional load, $\hat{q}$, to which the glass plate is subjected. The magnitude of the nondimensional load, $\hat{q}$, is defined in terms of the dimensionalized load, q, as follows:

$$\hat{q} = \frac{q(ab)^2}{Eh^4} \tag{3}$$

A full explanation of the derivation of the risk factor is presented elsewhere (Beason and Morgan 1984).

It is convenient to rewrite (2) as follows:

$$B = \kappa e^{J} \tag{4}$$

where

$$\kappa = \frac{k}{(ab)^{m-1}} (Eh^2)^m \left(\frac{t_d}{60}\right)^{m/16} \tag{5}$$

and

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$$J = \ln\left[R\left(m, \hat{q}, \frac{a}{b}\right)\right] \qquad (6)$$

Thus, (1) can be rewritten as follows:

$$P_f = 1 - e^{-\kappa e^J} \qquad (7)$$

Finally, (7) can be further simplified for small probabilities of failure as follows:

$$P_f \approx \kappa e^J \qquad (8)$$

The amount of error involved in the estimation of P_f by use of (8) is small as long as $P_f < 0.05$. This is easily demonstrated by substituting values of $P_f < 0.05$ into (7) and (8).

ASTM E 1300-94 incorporates an expression similar to (8). However, the value of κ that is incorporated in the ASTM E 1300-94 version of (8) does not include the load duration term, $(t_d/60)^{(m/16)}$. This term was purposely left out of the ASTM E 1300-89 equation when it was first introduced to reduce the complexity of the procedure. However, with the advent of proposed changes to existing wind load procedures ("Minimum" 1993), there is an increasing need to address load durations other than 60 s. Therefore, the writers recommend that ASTM E 1300-94 be revised to include the complete version of (5).

Use of GFPM

To use the GFPM, reasonable estimates of the surface flaw parameters, m and k, the plate geometry, the elastic properties of glass, and the duration of the load are required so that (5) can be used to evaluate κ. In addition, it is necessary to know the magnitude of J as a function of the m surface flaw parameter, the magnitude of the nondimensional load, $\hat{q}$, and the plate aspect ratio. Once κ and J are known, either (7) or (8) can be used to calculate the probability of failure of a particular glass plate.

The relationship between the surface flaw parameters and a particular set of glass strength data is complex. Examination of a wide range of theoretically generated glass strength data shows that the m surface flaw parameter is related to the coefficient of variation of the data. As m increases, the coefficient of variation decreases (Beason and Norville 1989). Further, these examinations show that the k surface flaw parameter is closely related to the mean of the glass strength data. Procedures for calculating the optimum set of surface parameters to model a particular set of glass strength data were presented by Beason and Morgan (1984).

There tends to be a significant variation in the magnitudes of the optimal surface flaw parameters calculated from the results of different glass strength samples. The primary reason for this variation is that the character of the surface flaws can be significantly altered by even moderate mechanical exposures. After significant discussion and debate within the ASTM forum, which included the review of numerous sets of glass strength data, knowledgeable glass engineers and researchers established the following set of surface flaw parameters to be used for glass design: $m = 7$ and $k = 2.86 \times 10^{-53}$ $N^{-7} \cdot m^{12}$ (1.365×10^{-29} $in.^{12} \cdot lb^{-7}$) ("Standard practice" 1994; Beason and Norville 1989). This set of surface flaw parameters is intended to reflect the surface condition of glass that has been subjected to normal in-service exposures. Use of these surface flaw parameters will result in an underestimation of the strength of freshly manufactured glass and an overestimation of the strength for glass that has been subjected to severe environmental exposures.

To use the GFPM, it is also necessary to have a convenient representation of the value of J as a function of the nondimensional lateral load and the plate geometry. ASTM E 1300-94 incorporates a single chart, which relates the variation of J to the plate aspect ratio and the magnitude of the nondimensional lateral load. This chart can be used for aspect ratios ranging from 1–5 and for values of the nondimensional lateral load, $\hat{q}$, ranging from 10–1,500. Fig. 1 presents a revised J chart for nondimensional lateral loads up to 3,000. The data used to construct Fig. 1 were developed using (7) and a modified version of the nonlinear plate solution by Vallabhan and Wang (1981).

The writers recommend that the J chart incorporated in ASTM E 1300-94 be replaced with Fig. 1. This change will double the magnitude of the lateral load that can be treated. This will greatly increase the flexibility of the optional method used to estimate the probability of failure of rectangular glass plates and allow the design of window glass subjected to a broader range of loadings.

The first step to evaluate the probability of failure of a particular glass plate is to use the geometry of the glass plate, the appropriate modulus of elasticity, the load duration, and (5) to evaluate the magnitude of κ. The true thickness of glass, h, should be used in this calculation. It should be noted that the true thickness of glass, h, used in this calculation is generally less than the nominal glass thickness. The only reliable means to determine the true thickness of a glass plate is through direct measurement. In the absence of direct measurement, the minimum allowable thickness as defined in ASTM C 1036-90 ("Standard specification" 1990) can be conservatively used to evaluate κ. Table 1 presents the ASTM C 1036-90 relationship between the nominal glass thickness and the minimum glass thickness.

Once the proper value of κ has been calculated, Fig. 1 can be used to determine the value of J corresponding to the glass plate aspect ratio, a/b, and the magnitude of the nondimensional load, $\hat{q}$, as calculated using (3). Finally, the probability of failure of the glass plate can be calculated using (7) or (8).

As an example of the use of this procedure, the probability of failure associated with 1,000 × 1,600 × 6 mm (39.4 × 63.0 × 1/4 in.) glass plate subjected to a 3-s duration load of 2.1 kPa is presented. First, (3) is used to calculate the magnitude of the nondimensional load, $\hat{q}$, as follows:

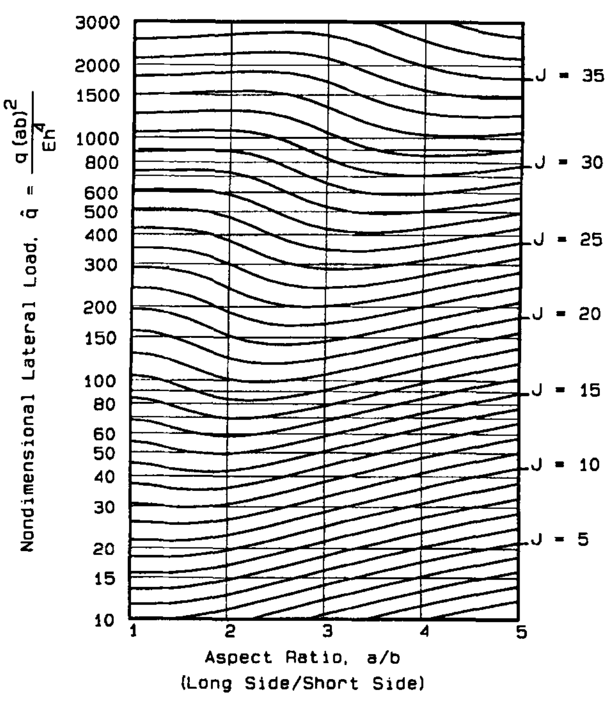

FIG. 1. Variation of *J* with Aspect Ratio and Nondimensional Load

TABLE 1. Minimum Glass Thickness

Nominal thickness (mm) (1)	Nominal thickness or designation (in.) (2)	Minimum thickness (mm) (3)	Minimum thickness (in.) (4)
2.5	3/32	2.16	0.085
2.7	[Lami]	2.59	0.102
3	1/8	2.92	0.115
4	5/32	3.78	0.149
5	3/16	4.57	0.18
6	1/4	5.56	0.219
8	5/16	7.42	0.292
10	3/8	9.02	0.355
12	1/2	11.91	0.469
16	5/8	15.09	0.594
19	3/4	18.26	0.719
22	7/8	21.44	0.844

Note: Information as presented in ASTM C 1036-90.

$$\hat{q} = \frac{(2.1 \text{ kPa})(1.0 \text{ m} \times 1.6 \text{ m})^2}{(71.7 \times 10^6 \text{ kPa})(0.00556 \text{ m})^4} \approx 78 \tag{9}$$

where the true thickness of the glass is conservatively estimated using data presented in Table 1. The aspect ratio of the glass plate is found as follows:

$$\frac{a}{b} = \frac{1{,}600 \text{ mm}}{1{,}000 \text{ mm}} = 1.6 \tag{10}$$

Fig. 1 is then entered with the results of (9) and (10) to estimate the value of J at about 17.2.

The proper value of κ is then found using (5) as follows:

$$\kappa = \frac{(2.86 \times 10^{-53} \text{ N}^{-7} \cdot \text{m}^{12})}{(1.0 \text{ m} \times 1.6 \text{ m})^6} (71.7 \times 10^9 \text{ Pa} \times 0.00556^2 \text{ m}^2)^7 \cdot \left(\frac{3}{60}\right)^{7/16} \quad \kappa \approx 1.21 \times 10^{-10} \tag{11}$$

The probability of failure of the glass plate is then estimated to be about 0.004 as follows:

$$P_f \approx (1.21 \times 10^{-10})(e^{17.2}) \approx 0.004 \tag{12}$$

As stated previously, if the glass plate is freshly manufactured, the actual probability of failure would be less than that given by (12), and if the glass plate has been subjected to severe in-service exposures, the actual probability of failure could be greater than that given by (12).

DUAL-UNIT GLASS THICKNESS SELECTION CHARTS

While the GFPM formulations presented above can be readily incorporated into a computer code to estimate the probability of failure of a glass plate subjected to a lateral load of specified duration, use of the formulations is not convenient for routine glass design. Routine glass design has traditionally been accomplished using glass thickness selection charts.

ASTM E 1300-94 currently presents glass thickness selection charts in both SI and U.S. customary units for the 12 common glass thicknesses presented in Table 1. This results in a total of 24 different glass thickness selection charts (Beason, unpublished research, 1988). At the time that the ASTM glass thickness selection charts were introduced, the glass industry was deeply entrenched in U.S. customary units. Thus, it was considered necessary to present individual charts for both sets of units. However, since that time, the use of SI units has become more accepted, and it is now appropriate to produce dual-unit glass thickness selection charts. A move to dual-unit charts will cut the total number of glass thickness selection charts in half.

Figs. 2–13 present dual-unit glass thickness selection charts for common glass thicknesses based on the GFPM. These newly developed glass thickness selection charts are based on a format similar to that used for the ASTM E 1300-94 glass thickness selection charts. This format was the result of considerable effort and discussion by those involved in the original formulation of the ASTM E 1300-89 glass thickness selection charts. The primary deviation from the ASTM E 1300-89 format is that the proposed charts incorporate SI and U.S. customary units in a single chart. The dual units are incorporated through the use of secondary axes. The plate areas, aspect ratios, and thicknesses presented are the same as those

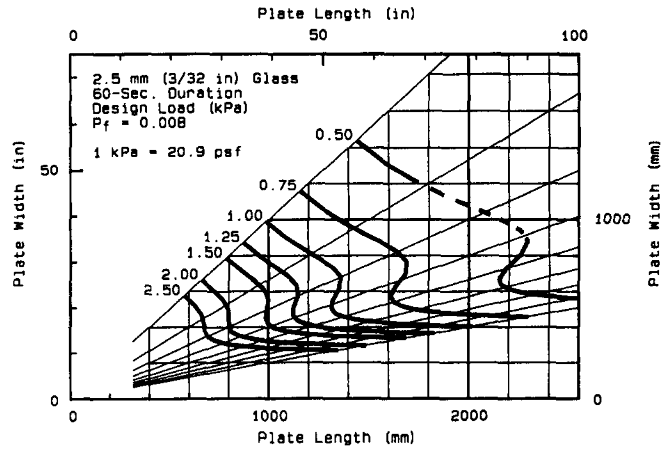

FIG. 2. Glass Thickness Selection Chart for 2.5 mm (3/32 in.) Annealed Glass

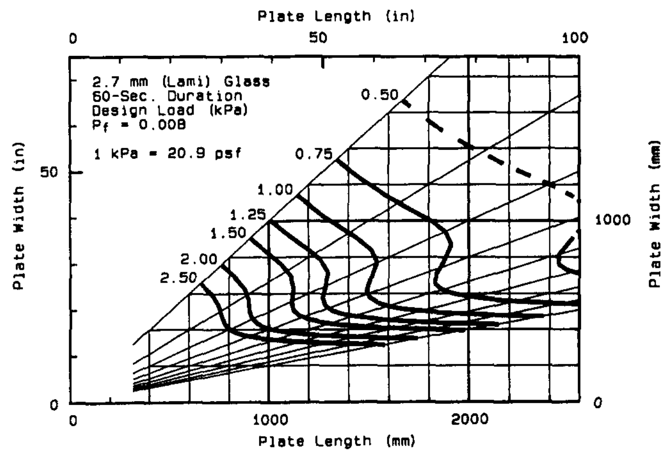

FIG. 3. Glass Thickness Selection Chart for 2.7 mm (Lami) Annealed Glass

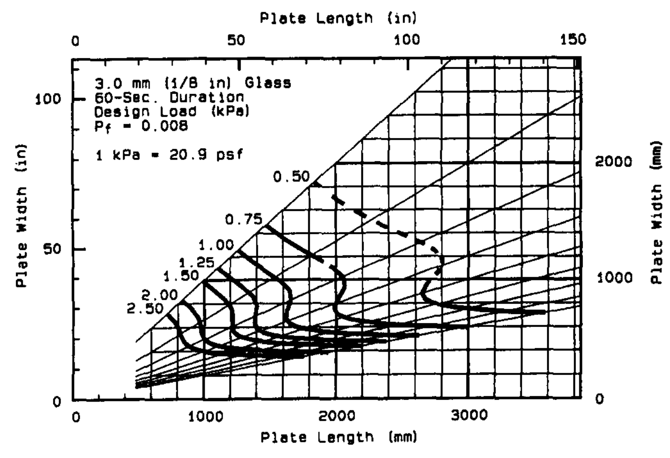

FIG. 4. Glass Thickness Selection Chart for 3.0 mm (1/8 in.) Annealed Glass

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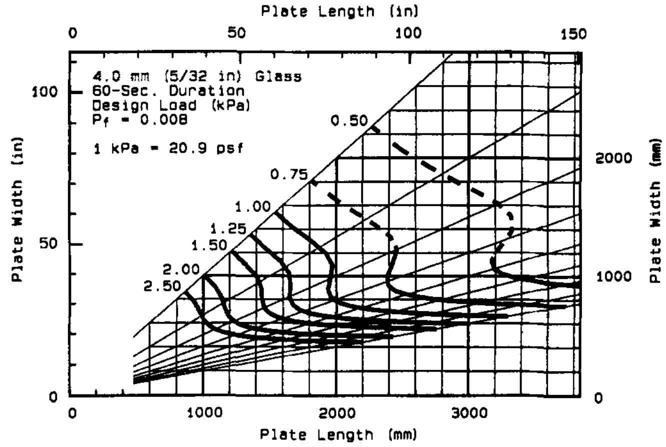

FIG. 5. Glass Thickness Selection Chart for 4.0 mm (5/32 In.) Annealed Glass

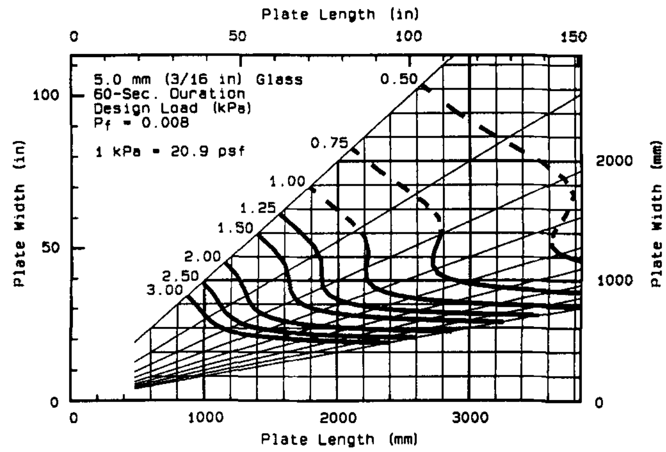

FIG. 6. Glass Thickness Selection Chart for 5.0 mm (3/16 In.) Annealed Glass

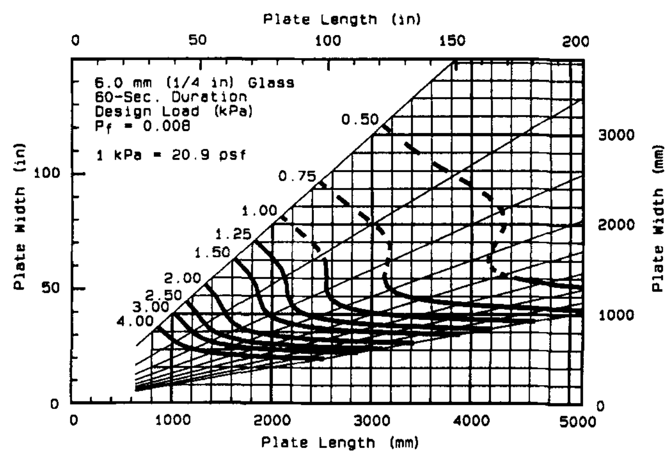

FIG. 7. Glass Thickness Selection Chart for 6.0 mm (1/4 In.) Annealed Glass

included in the original ASTM E 1300-89 glass thickness selection charts.

The new dual-unit glass thickness selection charts presented in Figs. 2–13 allow the 60-s duration design load associated with a probability of failure of 0.008 to be determined as a function of the glass thickness and the rectangular dimensions of the plate. The procedure to accomplish this is given as follows:

1. Select the proper glass thickness selection chart based on the nominal thickness of the glass.
2. Enter the horizontal axis of the chart at the point corresponding to the long rectangular dimension, *a*, and project a vertical line.
3. Enter the vertical axis of the chart at the point corresponding to the short rectangular dimension, *b*, and project a horizontal line until it intersects the vertical line in step 2.
4. Sketch a line of constant aspect ratio by connecting the point located in steps 2 and 3 with the origin of the graph.
5. Determine the 60-s duration design load corresponding

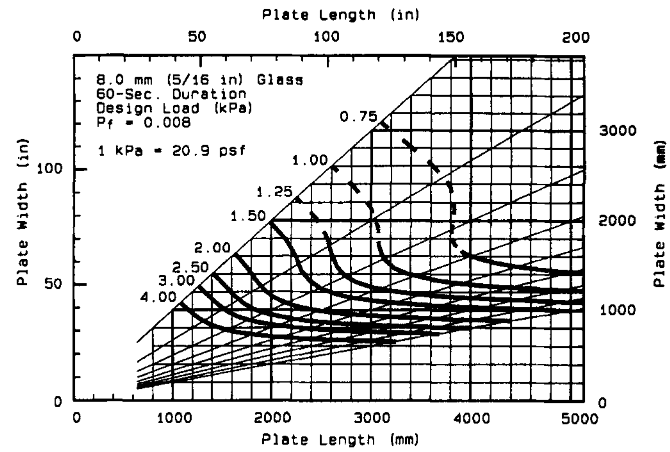

FIG. 8. Glass Thickness Selection Chart for 8.0 mm (5/16 In.) Annealed Glass

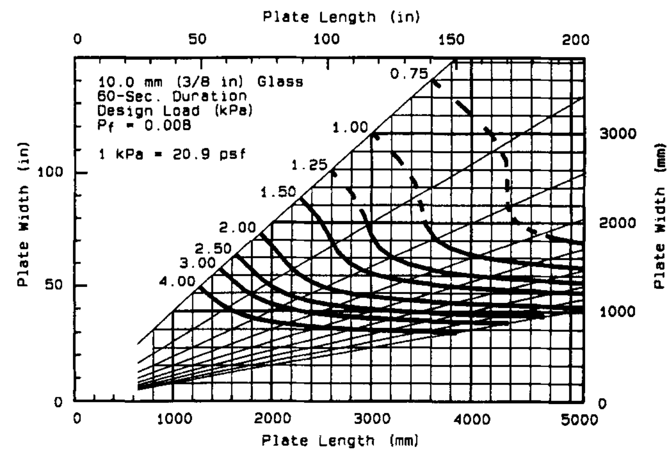

FIG. 9. Glass Thickness Selection Chart for 10.0 mm (3/8 In.) Annealed Glass

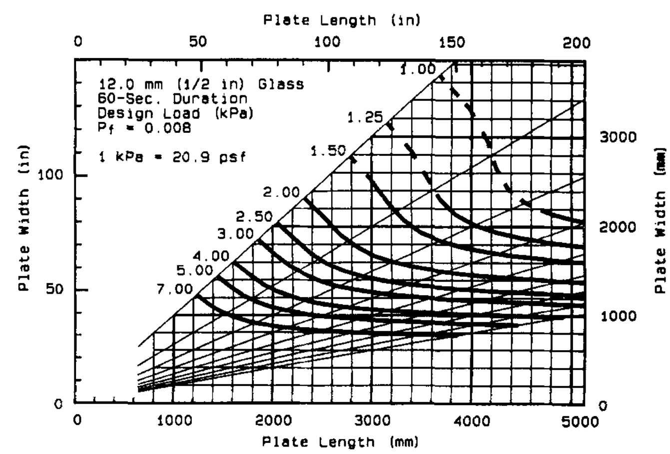

FIG. 10. Glass Thickness Selection Chart for 12.0 mm (1/2 In.) Annealed Glass

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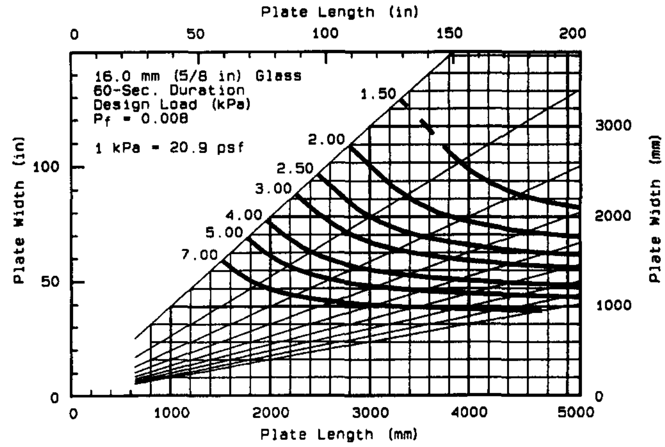

FIG. 11. Glass Thickness Selection Chart for 16.0 mm (5/8 In.) Annealed Glass

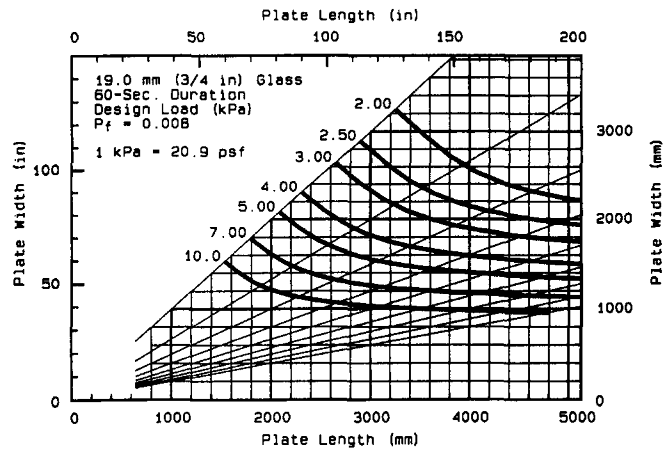

FIG. 12. Glass Thickness Selection Chart for 19.0 mm (3/4 In.) Annealed Glass

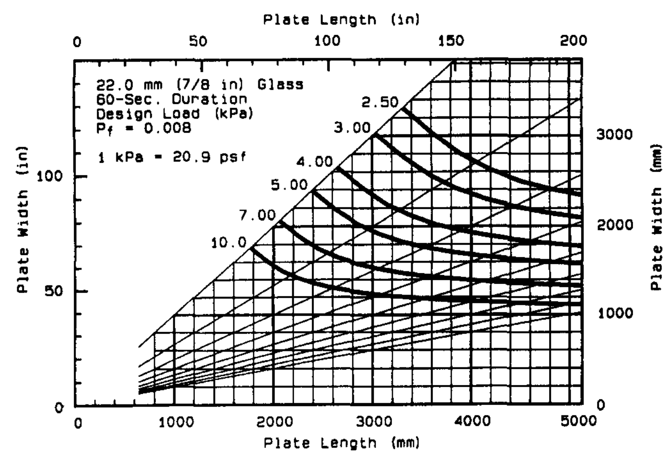

FIG. 13. Glass Thickness Selection Chart for 22.0 mm (7/8 In.) Annealed Glass

to a probability of failure of 0.008 by interpolating between the load contours along the line of constant aspect ratio.

6. If the 60-s duration design load determined in step 5 lies in an area of dashed lines on the chart, it is an indication that the maximum lateral deflection of the plate exceeds an arbitrary limit of 19 mm (0.75 in.).

To use U.S. customary units, the glass thickness selection chart is entered using the secondary U.S. customary axes and the design load is determined in kilopascals. The corresponding U.S. customary load in pounds per square feet is then determined by multiplying the SI load by 20.89 psf/kPa.

As an example of this process, consider a 1,000 × 1,600 × 6 mm (39.4 × 63.0 × 1/4 in.) glass plate. Fig. 7 contains the proper glass thickness selection chart. If steps 1–5 are followed, the 60-s duration design load for this glass plate is equal to about 1.9 kPa (40 psf).

CONCLUSIONS

This paper presents a brief review and update of the glass failure prediction model (GFPM). The GFPM is a theoretical procedure that allows the probability of failure of a glass plate subjected to a uniform lateral pressure loading to be determined as a function of the plate geometry, the duration of the loading, and the properties of the glass surface flaws. The GFPM serves as the technical basis for glass thickness selection charts presented in ASTM E 1300-94. This paper presents technical documentation for the existing ASTM E 1300-94 procedures and presents suggestions for improvements.

Glass thickness selection information presented in ASTM E 1300-94 can only be used for the treatment of 60-s duration loads. This presents a problem for designers who are forced to deal with loads of other durations. Therefore, improvements are suggested that allow glass thickness selection to be accomplished for load durations other than 60 s. In addition, new GFPM technical data are presented that double the maximum loads that can be considered with the ASTM E 1300-94 optional procedure for estimating the probability of failure for rectangular annealed glass plates.

A new set of dual-unit glass thickness selection charts that reflect the strength of glass subjected to 60-s duration loads is presented. These charts are similar to those currently incorporated in ASTM E 1300-94. However, by incorporating both SI and U.S. customary units into a single chart, the total number of glass thickness selection charts incorporated in ASTM E 1300-94 can be significantly reduced.

It is hoped that if the suggested improvements and changes are incorporated in ASTM E 1300-94, it can become a more valuable tool for designers.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

a = long dimension of rectangular plate;
a/b = aspect ratio of rectangular plate;
B = risk function;
b = short dimension of rectangular plate;
E = modulus of elasticity;
h = true thickness of glass;
J = natural logarithm of risk factor, $R(m, \hat{q}, a/b)$;
k = surface flaw parameter;
m = surface flaw parameter;
P_f = probability of failure of glass plate;
q = dimensionalized uniform lateral load;
$\hat{q}$ = nondimensionalized uniform lateral load;
$R(m, \hat{q}, a/b)$ = risk function;
t_d = duration of loading; and
κ = variable.

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