Damage assessment of curtain wall glass

H Puga[1], BA Olmos[2], L Olmos[2], JM Jara[2] and M Jara[2]

[1] Graduate student, UMSNH, 58030 Morelia, Michoacán, México
[2] Professor UMSNH, 58030 Morelia, Michoacán, México

E-mail: bolmos@umich.mx

Abstract. The failure prediction of simply supported annealed glass plates subjected to uniform loads is one of the main purposes in the design codes of the United States, Canada and the European Community. The methodologies and codes available in the literature are based on concepts and criteria applicable to the glass failure prediction; they evaluate the load associated to a specific probability of failure. The aim of this work is to estimate fragility curves for curtain glass under different uniform loads representative of the wind loads that they can be subjected, using the lifetime prediction model. The capacity of the structural elements was determined experimentally considering as-received annealed soda lime silica glass; this material is used in structural elements although the material is brittle and random. The capacity and demand are associated with the life time prediction model. The results let us understand the glass failure mechanisms of glass panels with different thickness, as well as assess their probability of failure by estimating fragility curves.

1. Introduction

The glass is a material with an important development on the techniques used for its manufacturing. The float glass process was developed in the 1050s by Alastair Pilkington. This technique allowed producing float glass elements with good qualities to be used in the engineering practice. However, the pioneering work of Griffith [1] showed that the glass surface flawed by having micro-cracks, which represented the main causes of their fragility and resistance randomness. These and other factors are accounted in the methodologies presented in the design codes of North America and Europe to estimate the glass panels' thickness for a design load. The structural design of curtain wall glass can be achieved using the ASTM E 1300-12a [2] in the United States, the CAN/CGSB 12.20-M89 [3] in Canada, and with the EN 13474 [4] and Haldimann's life time prediction model [5] in Europe. All of these methodologies relay on the estimation of the failure probability of the glass panels.

The standard ASTME 1300-12a offers a wide variety of graphics to estimate the glass thickness required for a specific problem. The fundamental concepts used for the development of those curves is the glass failure prediction model proposed by Beason in 1980 and the Vallavhan's research [6], to calculate deflections accounting for the non-geometric linearity's. The glass failure prediction model was developed based on two flaw surface parameters, characterizing the surface condition and a parameter dependent of the crack velocity. The design aids correspond to glasses characterized with a surface condition of $m=7$, $k=2.86\times10^{-53}N^{-7}m^{12}$, elastic modulus of 71.7 GPa and by the glass thickness [5]. Basically, the standard is related to define the load resistance for different glass types with rectangular geometry supported continuously in one, two, three or four sides. The resistance load

corresponds to a probability of failure of 0.8% for load duration of 3 seconds. The design load can be one or a combination of the effects of wind, snow, earthquake and glass' self-weight whereas the load is assumed to be not larger than 15 kPa. Two factors define the load resistant: the glass type factor and the non-factored load. The first one accounts for glass type and load duration whereas the second is for the non-factorized load with duration of 3 seconds.

The Canadian standard, CAN/CGSB 12.20-M89 has a similar methodology to the ASTM E1300-12a, both based on the glass failure prediction model [6], and considering glass elements under uniform lateral loads as well as a failure probability of 0.8%. The main difference between them is the load duration assumed, 60 seconds in this case vs. 3 seconds, to estimate the load resistance.

In 1999 the European Committee for Standardization (CEN) published the standard EN 13474-1 that states the general bases for the design of glass elements. The second edition, prEN 13474-2 presents a design method for curtain walls. The third edition of the standard is under revision, prEN 13474-3, where the glass' strength can be estimated with a general methodology or with a detailed methodology based on experimental tests. The parameters used in this standard relay on two crack velocity parameters estimated based on coaxial double ring tests with constant stress rates; with these parameters, the fundamental surface parameters can be calculated using the expression defined in the standard.

The life time prediction model [5] is a generalized probabilistic methodology that can be used for any type of structural glass elements (girders, columns and plates) and load condition. The linear elastic fracture mechanics and the theory of probability are the foundations of the model. A thoroughly consideration of the variables dictating the glass strength behavior (phenomenon of stress corrosion causing subcritical growth of surface flaw, the time-dependent behavior of flaws with random depth, location and orientation) is considered to establish a risk integral approach. The methodology is powerful because of the consideration of many random variables that are simplified in design codes that allows to estimate closely, the real glass behavior for different types of structural elements. However, it is necessary to extend the knowledge of probability and glass mechanics, and also conduct experimental studies which increase its implementation cost and its generalization for the practitioner practice. In spite of these, there is a simplification of the model [5] under research to be considered as standard in a close future.

The aim of this work is to develop general design aids, as the ones presented on the standard ASTME 1300-12a, applying the methodology for the use of the practitioner engineer. First we lead an experimental research program that characterizes the mechanical properties of silica glass for the estimation of the probabilistic parameters [7] used to estimate the fragility curves presented in this work, and later the fragility curves are the data base needed to create the design aids, results that will be reported in a following work. The results presented in the present study show increases on the load resistance by curtain glass panels as a function of their thickness, and the design loads are about 25% lower when considering the probability of failure associated to the European code than the ones related to the probability of failure of the American and Canadian codes.

2. The lifetime prediction model

The life time prediction model [5] is based on concepts of the linear elastic fracture mechanics and the theory of probability where it is assumed a random crack distribution in the glass surface with a random length and number. The main hypotheses of the method are: the glass surface has a random number of cracks with random depth; the cracks' depth can be represented with a Pareto probability density function; the cracks' behavior is independent of the one for the neighbor cracks; the cracks' location and orientation have the same probability to be in any location on the glass surface, so they can be defined with a uniform probability density function; the failure mode I defined for the linear fracture mechanics is assumed to be accurate; and the probability of failure accounts only for tensile strengths, neglecting the compression effects. The theory underneath is:

1. The relationship between crack velocity and stress intensity is defined with an equivalent formulation based on the linear crack velocity parameter v_0, a dimensionless crack velocity parameter n, the stress intensity factor, K_I, and the material constant, K_{Ic}, that is well known. The relationship between v_0 and K_I is simplified into three regions defining the environment influence. Region I defined linear behavior with a small slope since the subcritical crack growth is slow and depends on the environmental conditions; Region II defined with a constant value where v is independent of K_I but depends on the amount of humidity in the environment; and Region III defined linear behavior with a steep slope where v is independent of the environment. It is assumed region I because of the ratio of the size glass elements in buildings and the surface flaws expected for the service life time.

$$v = v_0 \left(\frac{K_I}{K_{Ic}}\right)^n \tag{1}$$

2. The basic rule of glass failure: "A glass element fails, if the stress intensity factor K_I due to tensile stress at the tip of one crack reaches its critical value K_{Ic}", [2]. It is expressed by the relationship among the stress intensity factor K_I, the nominal tensile stress normal to the crack's plane σ_n, a correction factor Y, and the crack depth a, as:

$$K_I = Y\sigma_n\sqrt{\pi a} \geq K_{Ic} \tag{2}$$

which is the base to define implicitly the critical strength σ_c and critical crack depth a_c considered for the development of the integral risk.

3. A subcritical crack growth and lifetime is estimated by differentiating with respect time the crack depth that after substitution, integration and algebraic manipulation led to the risk integral expressed in equation (3) for a time failure or lifetime t_f.

$$\int_0^{t_f} \sigma_n^n(\tau)d\tau = \frac{2}{(n-2)v_0 K_{Ic}^{-n}\left(Y\sqrt{\pi}\right)^n a_i^{(n-2)/2}} \tag{3}$$

4. The previous concepts are extended to a random surface flaw population assuming a constant stress and no subcritical crack growth, being the failure probability of a crack the probability that its random size a is larger than the critical crack depth a_c:

$$P_f = \int_{a_c}^{\infty} f_a(a)da = 1 - F_a(a_c) \tag{4}$$

By defining the adequate probability density function to each of the random variables defined and extending the concepts to a multimodal failure criterion, to a time-dependent loading and to account for subcritical crack growth, the lifetime prediction model is defined with [2],

$$P_f(t) = 1 - exp\left[-\frac{1}{A_0}\int_A \frac{2}{\pi}\int_{\varphi=0}^{\frac{\pi}{2}}\left[\max_{\tau\in[0,t]}\left[\left\{\left(\frac{\sigma_n(\tau,\vec{r},\varphi)}{\theta_0}\right)^{n-2} + \frac{\int_0^{\tau}\sigma_n^n(\tilde{\tau},\vec{r},\varphi)d\tilde{\tau}}{U\cdot\theta_0^{n-2}}\right\}^{\frac{1}{n-2}}\right]\right]^{m_0} dAd\varphi\right] \tag{5}$$

where P_f is the failure probability, A_0 is a unit surface area (A_0=1 m^2), A is a surface area of the glass element, $\sigma_n(\tau,\vec{r},\varphi)$ is an in-plane surface stress component normal to a crack orientation φ at the point $\vec{r}(x,y)$ on the surface and at a time τ, t is the point time, K_{Ic} is the fracture toughness, Y is the geometry factor, v_0 and n are the velocity parameters, θ_0 and m_0 are the surface condition parameters, U is a coefficient containing parameters related to fracture mechanics and subcritical crack growth, defined by:

$$U = \frac{2K_{Ic}^2}{(n-2)\cdot v_0 \cdot Y^2\pi} \quad \text{(units of stress}^2 \times \text{time)} \tag{6}$$

To implement this methodology, we conducted dynamic fatigue test trough a suitable coaxial double ring test setup for new silica glass specimens, with the aim to determine the failure load and the maximum deflection associated. The experimental results were correlated with an analytical model of the tested plates under uniform load, to validate the probabilistic parameters determined during this step. Finite element models for 672 glass plates where developed to calculate the tensile stresses on the plates' surface. The lifetime prediction model was applied to the data generated to get the fragility curves; from them, it was estimated the load associated to two failure probabilities, 0.8 and 0.12%, commonly used on the design codes, it was estimated in order to analyze the structural behavior of curtain glass.

2.1. Silica glass characterization

The fatigue dynamic tests were based on the Standard Test Method for Monotonic Equibiaxial Flexural Strength of Advanced Ceramics at Ambient Temperature [8], also known as coaxial double ring test setup. The specimens correspond to new silica glass with quadrilateral section of 200mmx200mm and thicknesses of 3, 4, 5, 6, 8, 10, 12 and 19 mm. Ten specimens for each of the geometries were tested up to failure on an Instron-5500R machine under a load failure rate of 79 kN/min and ambient conditions, the details of the experimental work can be found in [7]. Here only the generalities and the final results are reported. The principal stresses that lead to the specimen failure were determined from the experimental test. This information was used to estimate the parameters related to the silica glass surface under ambient conditions (m_0=5, θ_0=59.78 MPa). Figure 1 shows a load-deflection curve for some of the specimens tested and a picture of one of the failure modes presented by the specimens.
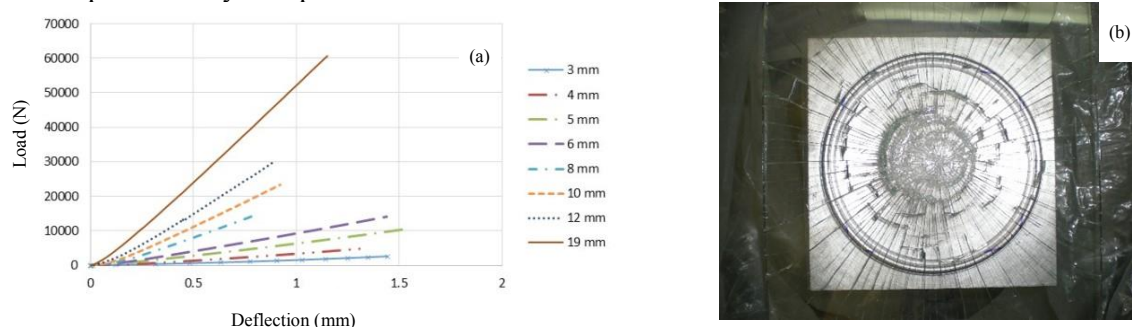

Figure 1. Load vs. deflection curve for some of the specimens (a), and failure mode of a glass specimen with 5 mm of thickness (b).

2.2. Numerical model

For an accurate representation of glass plates, it is required to account for the geometric nonlinearity described by the theory of large deflections when the deflections are larger than one third of the plate's thickness. This problem must be considered on glass plates because the aspect ratio led to inaccurate results when applying the linear plate's theory of Kirchoff that neglects the strains at the middle of the edges and the membrane stresses. The ANSYS software was implemented to create the numerical models with the "Static Structural" module considering the glass as an isotropic material, and accounting for the geometric non linearity that could be present in the plates. Previously to build all them to estimate the fragility curves, there were developed in ANSYS some of the specimens tested to validate the numerical models. After the validation, 672 curtain glass models were built varying the glass plates' size and thickness and assuming them simple supported on their four sides. The cases studied consider width to depth ratio (a/b where a>b) of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0, and the curtain glass thicknesses of 2.5, 3.0, 4.0, 5.0, 6.0, 8.0, 10, 12, 16, 19, 22 and 25 mm. The cases are limited by the maximum glass curtain size offered by the industry, 2.5x3.5 m, as

the commercial thicknesses as well, NOM-146-SCFI-2001. Based on these, the glass plates' width and depth selected cover surface plates' areas in the range of 0.375 to 9.375 m^2.

To optimize the time required for the analyses and taking advantage of the plates' symmetry, each of the curtain plates was represented with a quarter of the plate modeled with an isotropic elastic shell finite elements type Shell 181. The finite element sizes vary from 10x10 mm to 30x30 mm. The material properties for the results presented in this work are: elastic modulus of 74000 MPa, Poisson ratio of 0.23 and specific density of 2500 kg/m^3. A fixed condition was considered in the nodes located at the plate edges with an exception of the degree of freedom related to the displacement running out of the glass plate plane. The simple supported condition, recommended in [3] and [4], led to the maximum deflection that can reach a glass plate, representing also the large effects of geometric nonlinearities.

The numerical models were subjected to a uniform pressure under 20 load stages with increments of 0.001 MPa. Since the uniform load value required to cause the failure of the glass plates was unknown, the maximum intensity considered in each of the analyses was 0.02 MPa. Figure 2 shows the results for one of the models under a uniform load of 0.02 MPa.
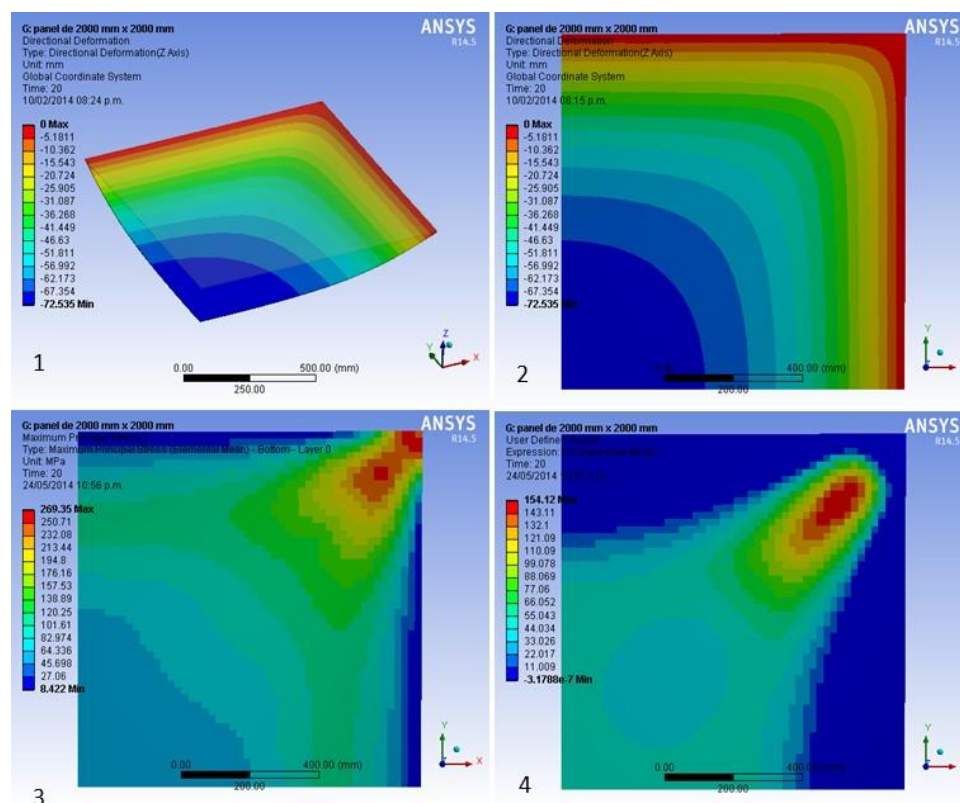

Figure 2. Finite element model for a curtain glass under a uniform pressure of 0.02 MPa: 1) Deformed plate shape, 2) Maximum deflection at the center of the plate (72.5 mm), 3) Maximum principal stress plate distribution, and 4) minimum principal stress plate distribution.

The estimation of the fragility curves based on the lifetime prediction model needs a great number of data defining the stresses on the plates' surface subjected to the entire possible uniform loads. Because this implies an infinite number of analyses, regression analyses were used to extrapolate the stresses associated to loads not considered in our models. This is possible, due to the elastic behavior of the glass associated to a linear load or uniform pressure. Figure 3 shows the regressions associated to the principal stresses.
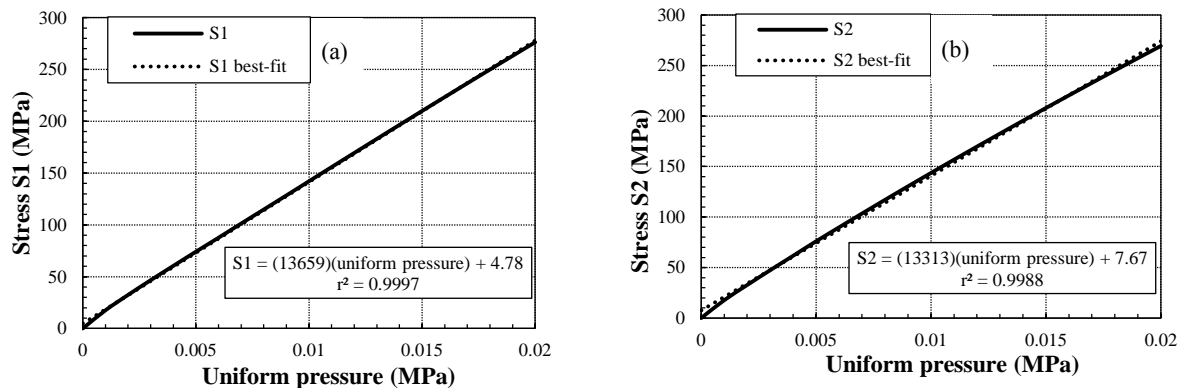
Figure 3. Uniform pressure vs. principal stresses and adjusted with a linear regression, (a) S1 and (b) S2.

3. Fragility curves

Fragility is the probability to reach or to exceed a limit state of behavior. It is defined with equation (5) and programmed using the Matlab software that allows generating a data base relating glass plate sizes with a uniform pressure, associated with a probability of failure. Table 1 shows the parameters considered in the lifetime prediction model.

Table 1. Glass curtains' mechanical properties and parameters considered for the fragility estimates.

Parameter(s)	Value
Critical stress intensity factor (K_{IC})	23.7172 MPaxmm$^{0.5}$
Correction factor (Y)	1.12 (dimensionless)
Crack velocity parameters (v_0, n)	v_0 = 6 mm/s
θ_0	n = 16 (dimensionless)
m_0	59.88 MPa
Young's modulus (E)	74 000 MPa
Uniform load time duration (t)	3 s
Sub-area (A_i)	Function of shell size (mm^2)
In-plane principal stresses $S1$ and $S2$	From the finite element (MPa)

The graphs plotted on figure 4 show representative fragility curves for curtain glass panels with sizes of 2500mmx2500mm and 3500mmx500mm, and thicknesses of 2.5, 8 and 25 mm respectively in rows 1 to 3. The results correspond to the uniform pressure on the plates associated with a probability of failure, and it is also reported the uniform pressure for the probabilities considered on the design codes of North America (0.008) and Europe (0.0012). The results presented in figure 4 show that for a defined probability of failure the load needed to reach a limit state increases as the plate thickness increases, and the quadrilateral plates have less strength than the rectangular ones. To confirm these results, table 2 resumes the failure probability for all the thicknesses considered in these sets of plates.

Figure 5 summarizes the fragility curves for all the thicknesses (h) considered for curtains with size of 2000mmx2000mm, plotting only the failure probability interval used with design purposes. The results confirm that the increase of the plate thickness increases the load capacity. It is noticeable that the curtain glass strength associated with the probability of failure adopted by the European code

(0.0012) is in general 25% lower than the one assumed with the American code (0.008), when the lifetime prediction model is implemented.
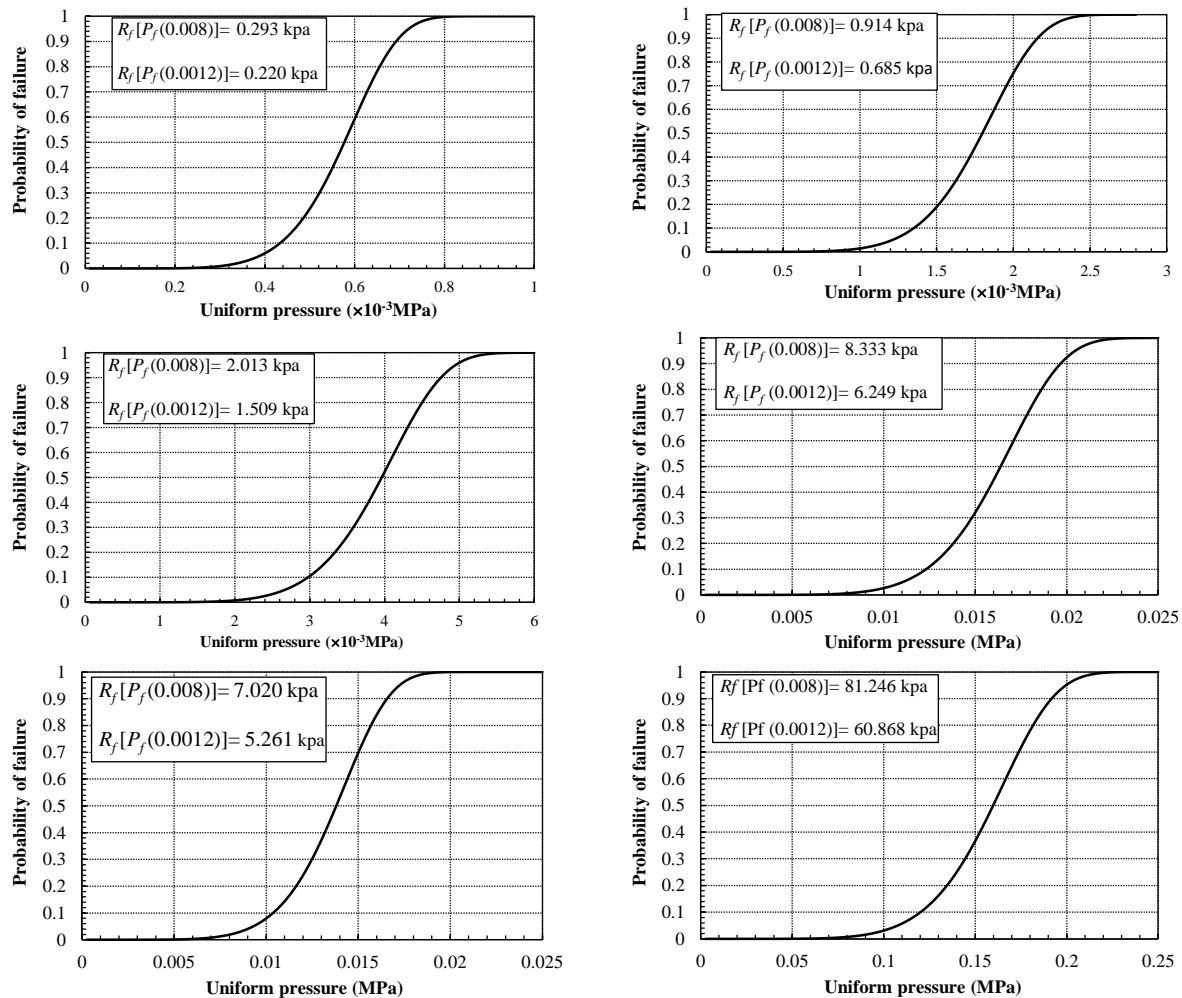

Figure 4. Fragility curves for a uniform pressure for curtain glass plates of 2500 mm x 2500 mm (first column), 3500 mm x 500 mm (second column), and thicknesses of 2.5 (first row), 8 (second row) and 25 mm (third row).

Table 2. Uniform pressure, R_f (kPa), on the curtain glass panels to rich a design failure probability.

Curtain size	R_f [P_f(0.008)]	R_f [P_f(0.0012)]	Curtain size	R_f [P_f(0.008)]	R_f [P_f(0.0012)]
2500x2500x3	0.375	0.281	3500x500x10	13.016	9.751
3500x500x3	1.207	0.905	2500x2500x12	3.138	2.351
2500x2500x4	0.723	0.541	3500x500x12	18.743	14.038
3500x500x4	2.096	1.569	2500x2500x16	4.888	3.661
2500x2500x5	0.974	0.730	3500x500x16	33.309	24.977
3500x500x5	3.259	2.441	2500x2500x19	5.397	4.074
2500x2500x6	1.398	1.047	3500x500x19	46.984	35.202
3500x500x6	4.693	3.515	2500x2500x22	6.156	4.614
2500x2500x10	2.607	1.953	3500x500x22	62.933	47.143

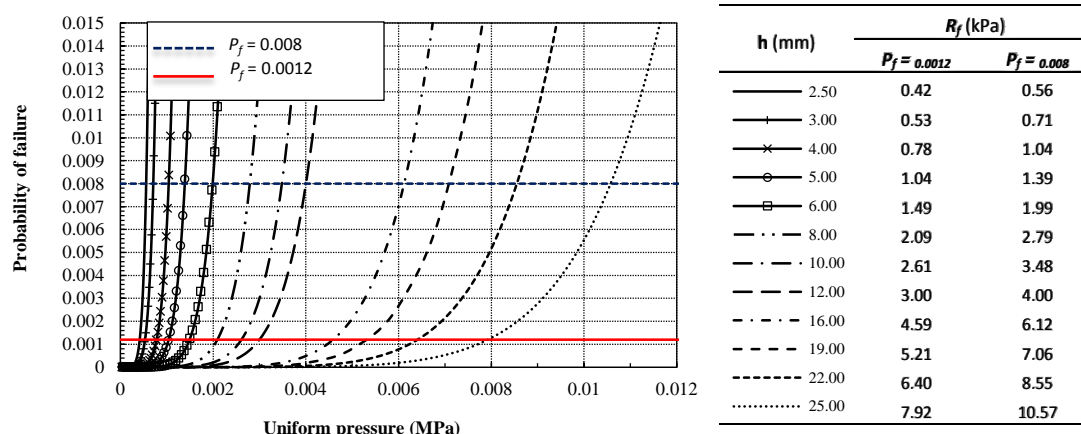| h (mm)	R_f (kPa)	
	$P_f = 0.0012$	$P_f = 0.008$
——— 2.50	0.42	0.56
—+— 3.00	0.53	0.71
—×— 4.00	0.78	1.04
—○— 5.00	1.04	1.39
—□— 6.00	1.49	1.99
— · · — 8.00	2.09	2.79
— · — 10.00	2.61	3.48
— — 12.00	3.00	4.00
— · — 16.00	4.59	6.12
— — 19.00	5.21	7.06
- - - - - 22.00	6.40	8.55
· · · · · · 25.00	7.92	10.57

Figure 5. Fragility curves for a uniform pressure of glass plates' 2000 mm x 2000 mm x h mm.

4. Conclusions

672 curtain glass finite element models were developed using the ANSYS software. The models are representative of plates' sizes built by the glass industry. We developed functions to interpolate and extrapolate the stresses on the shell plates for different pressures with an extended data base to estimate the fragility curves. We also programed the lifetime prediction model offering a tool to evaluate any fragility curve as a function of the glass' surface parameters [7]. The load resistance of curtain glass panels increases with the glass thickness increase. We also found that the failure probability proposed by the European code conducts to design loads 25% lower than the loads obtained using the failure probability stated in the American and Canadian codes. The next step is to develop curve design aids using the glass probability of failure estimated with the lifetime prediction model, research that will be published posteriorly.

5. References

[1] Griffith A. A. (1920) The Phenomena of Rupture and Flow in Solids *Philosiphical Transactions, Series A.* **221** 163–198

[2] ASTM E 1300-12a (2012) *Standard practice for determining load resistance of glass in building.* American Society for Testing Materials, EUA, 1–59

[3] CAN/CGSB-12.20-M89 (1989) *Structural design of glass for buildings.* Canidian General Standards Board, Canada, 55

[4] EN 1374-1 (1999) *Vidrio para la identificacion-diseno de acristalamientos-Parte 1: Base general de calculo.* Comite Europeo de Normalizacion, enero, 1–29

[5] Haldiman M. (2006) *Fracture strength of structural glass elements-analytical and numerical modelling, testing and design.* PhD Dissertation No. 3671, Swiss Federal Institute of Technology Lusanne

[6] Beason W.L. and Morgan J.R. (1998) Glass Failure Prediction Model *Journal of Structural Engineering, ASCE.* **110 (2)** 197–212

[7] Puga H. (2014) *Modelo de prediccion de falla de cortinas de vidrio.* Thesis, Universidad Michoacana de San Nicolas de Hidalgo

[8] ASTM C 1499-05 (2005) *Standard test method for monotonic equibiaxial flexural strength of advanced ceramics at ambient temperature.* American Society for Testing Materials, EUA, 1–11