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Methodology to develop design aids of simple supported glass panels based on a probabilistic approach and experimental tests

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ABSTRACT

The use of glass in buildings, as structural element, has spread around the world. The increasing demand requires to conduct analytical and experimental studies to assess the glass structural behavior and its failure strength. This work determines design aids based on the life time prediction model for new annealed glass collected in Mexico, to estimate its strength and maximum deflection, assuming a probability of failure as function of the glass panel's geometry (width, length and thickness) and surface parameters. The glass surface parameters are determined through experimental tests and numerical finite element models. These results allowed the development of a set of design aids for new annealed glass that can be used in the design of glass windows. The study includes the definition of a correction factor that accounts for the effects of changing the elastic modulus on the glass panel strength, as well as an expression to estimate the maximum deflection at the center of the glass panel.

1. Introduction

Buildings, bridges and other structures are usually made of materials like reinforced concrete, steel or wood. Regulation codes specify the minimum standards to be used for the analysis and design of these structures. The use of glass elements in civil infrastructure have been usually limited to nonstructural elements; it is not long ago that modern architecture started using glass as structural element, leading to practitioner engineers and researchers the task of establishing the design rules to assess the expected performance under static and dynamic loads, including impact by flying projectiles and hard objects [22]. Several authors have proposed methodologies to predict the glass strength [4,8,9,11,13,17,18,21,24,29,27,32]. Most of the current works have as theoretical bases the pioneering work of Griffith [16], who showed that micro-cracks on the glass surface are strongly related to the resistance randomness effects and represent the main cause of the glass fragility. Design codes such as [3,10,14] are examples of the advances on the glass behavior knowledge around the world. The methodologies rely on the estimation of the failure probability of glass panels.

The standard ASTME 1300-12a offers a wide variety of graphs to estimate the expected maximum deflection and the glass thickness. The fundamental concepts used for the development of those curves are the glass failure prediction model proposed by Beason in 1980 and the Vallabhan's research [28], which considers non-geometric linearity's to calculate deflections. The glass failure prediction model was developed based on flaw conditions, characterized by two parameters, and the crack velocity (rate of change of crack size with time). The design aids were developed assuming a surface condition characterized with parameters $m = 7$, $k = 2.86 \times 10^{-53}\ \mathrm{N}^{-7}\ \mathrm{m}^{12}$ and elastic modulus of 71.7 GPa [9]. Basically, the standard defines the load resistance for different glass types with rectangular geometry supported continuously in one, two, three or four sides. The load capacity corresponds to a probability of failure of 0.8% for a load duration of three 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 less than 15 kPa. Two factors define the load resistance: the glass type factor and the non-factored load. The first one accounts for glass type and load duration whereas the second considers the non-factorized load with duration of 3 s.

The Canadian standard, CAN/CGSB 12.20-M89 uses a similar methodology to the ASTM E1300-12a, both are based on the glass failure prediction model [5], and considered glass elements under uniform lateral loads and a failure probability of 0.8% [13]. The main difference between the standards is the load duration considered to estimate the load resistance, 60 s (CAN) versus 3 s (ASTM).

In 1999 the European Committee for Standardization (CEN) published the standard EN 13474-1 that states the general bases

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for the design of glass elements. The second edition, prEN 13474-2 presents a design methodology for curtain wall, and the third edition of the standard, prEN 13474-3, is under revision. In the latter, the glass' strength can be estimated with a general methodology or with a detailed methodology based on experimental tests. The standard proposes an expression to obtain the fundamental surface parameters based on two crack velocity parameters determined from coaxial double ring tests, conducted under constant stress rates.

The life time prediction model (LTPM) is a generalized probabilistic methodology that can be used for any type of structural glass elements (girders, columns and plates) and load conditions [11,17,18,21]. The linear elastic fracture mechanics and the theory of probability are the bases of the model. A thoroughly consideration of the variables dictating the glass strength behavior (the 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 it accounts for many random variables that commonly are simplified in design codes, allowing an accurate estimation of the real glass behavior for different types of structural elements. However, this methodology requires the knowledge of probability, glass mechanics, and also experimental studies to implement it, reducing the possibilities of a generalized use by practitioner engineers. In spite of these, there is a simplification of the model under research to be considered as standard in the near future [17].

The aim of this work is to develop general design aids based on the LTPM to be used by practitioner engineers. To generalize the results, the design aids follow the format presented by the standard ASTME 1300-12a. To achieve the objective, first, researchers led an experimental campaign to characterize the mechanical properties of annealed glass, in order to determine the probabilistic parameters to assess the glass panels' fragility curves. These curves are the tool needed to generate a database to estimate the design aids. The results, glass panels' probability of failure and the expected maximum vertical deflection at the center of the glass panel, are summarized in graphs to calculate the maximum load pressure and vertical deflection that a rectangular glass panel is expected to resist, for a specific elastic modulus and a failure probability of 0.008. Furthermore, a careful parametric study allowed us to propose empirical equations to extrapolate the glass panels' strength and the associated vertical deflection for glass panels with an elastic modulus different to 74 GPa. The results show that through a correction factor it is possible and easy to capture the effects caused on the glass strength and vertical deflection due to a different glass elastic modulus. A comparison between the exact solution and the approximated one is presented to show the accuracy of the empirical equation. In addition to the practical and general applications of the design aids, this study is a starting point on the glass behavior research in Mexico.

2. Theoretical bases

2.1. American and Canadian design aids

The American standard ASTM E-1300-12a [9] and the Canadian standard [10,13] offer design aids to select the thickness of a glass panel. Both codes are based on the glass failure prediction model (GFPM) proposed by Beason [5] and Beason and Morgan [7]. Their development required a considerable number of experimental studies of new and existing glass panels, and the use of a probabilistic methodology. The GFPM allows estimating the risk of failure as a function of the glass surface condition and the stress distribution based on the brittle material failure theory [9]:

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

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

$$R\left(m,\hat{q},\frac{a}{b}\right) = \frac{1}{ab}\int_0^a\int_0^b\left[c(x,y)\hat{\sigma}(\hat{q},x,y)\right]^m dxdy \tag{3}$$

$$\hat{q} = \frac{q(ab)^2}{Eh^4} \qquad \hat{\sigma}(\hat{q},x,y) = \frac{\sigma(q,x,y)ab}{Eh^2} \tag{4}$$

where a and b are the dimensions of a rectangular plate ($a > b$), h is the glass plate thickness, m and k are the glass surface parameters, estimated from experimental tests of controlled glass plates up to failure; these parameters capture the severity and distribution of surface flaws (Weibull's parameters). t_d is the load duration, E is the glass elastic modulus, $R(m,\hat{q},a/b)$ is known as the risk factor, $\sigma(q,x,y)$, the maximum principal tensile stress expressed as a function of the out-of-plane loading on the glass panel, $c(x,y)$ the biaxial stress correction factor, and (x,y) is a location point within the glass plate surface.

In the cases of annealed and laminated glasses under a sustained load of 60 s, the design aids allow to account for a different load time duration when estimating the glass thickness required to support a uniform pressure. The results assume a probability of failure of 0.008 with a confidence level of 0.95.

2.2. Lifetime prediction model

Jakus et al. [21] combined the Weibull distribution with time-to-failure relations to assess glass' fatigue parameters. Later, Helfinstine [18] proposed a lifetime prediction model (LTPM) combining a strength distribution with delayed failure relationships. More recently, Carré and Daudeville [11] used a probabilistic model in association with a subcritical crack grow model to predict annealed glass failure strength, and Haldiman [17] developed a probabilistic LTPM for structural glass elements based on concepts of linear elastic fracture mechanics. The model relies on Eqs. (5) and (6) [17]. Eq. (5) relates stress intensity factor (K_I) to nominal tensile stress normal to the crack's plane (σ_n), and Eq. (6) defines the crack velocity (υ) as function of subcritical crack growth rate and stress intensity factor. The theoretical aspects for a single surface flaw came from the linear elastic fracture mechanics (LEFM), where the works of Griffith [16], Irwin [19] and others [11,18,21] allowed the development of the basic concepts ruling the glass failure that can be expressed in words as: a glass element fails, if the stress intensity factor K_I due to a tensile stress at the tip of one crack reaches its critical value, K_{IC}. The LEFM assesses the brittle failure behavior of glass through the propagation of one dominant crack in mode I; this mode represents the crack failing under tensile stress. Eq. (5) assumes that the dominant surface crack is semielliptical and orthogonal to the crack surface.

$$K_I = Y\sigma_n\sqrt{\pi a} \tag{5}$$

$$\upsilon = \upsilon_0\left(\frac{K_I}{K_{IC}}\right)^n \tag{6}$$

K_I and σ_n were already defined, Y is a geometry factor that is a function of the flaw geometry. This study assumes a semielliptical crack's geometry with Y value of 1.12 [20], a is the crack depth, υ_0 is the linear crack velocity parameter, K_{IC} is a material constant known as the critical stress intensity factor or fracture toughness, and n is a dimensionless crack velocity parameter. The K_{IC} factor is the stress intensity factor that leads to instantaneous failure, also known as the Irwin's fracture criterion:

$$K_I \geqslant K_{IC} \tag{7}$$