Engineering Structures 79 (2014) 244–255

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Strength prediction of annealed glass plates – A new model

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ARTICLE INFO

Article history:
Received 14 November 2013
Revised 8 August 2014
Accepted 10 August 2014
Available online 3 September 2014

Keywords:
Glass plate
Flaws
Brittle material
Fracture mechanics
Laboratory testing
Probabilistic
Modeling
Structural design
Cracking
Failure

ABSTRACT

A new model for assessing the strength of structural members made of annealed glass plates is presented. The model refers to a glass plate that is supported at its ends and loaded by a given loading system. To fully determine the mechanical behavior of the glass plate, a flaws distribution function is presented, from which the critical stress distribution is calculated. These critical stresses determine the local ultimate resistance of the plate. The model determines the flaws distribution over the area of a large basic plate, from which plates of different sizes are cut out. Each cut out plate is characterized by a different map of flaws that is distributed over its surface and it behaves differently as a result. The flaws shape, size and location determine the critical tensile stresses that are required for crack opening. These critical stresses are compared with the growing stresses during loading, to determine at which point and at what loading level fracture is initiated. The model is capable of predicting the tensile strength distribution of a large group of glass plates of a given geometry and boundary conditions. The model provides much information concerning the probabilistic distribution of the tensile strengths and the location of the fracture origin.

For an examined case the model yields an almost symmetrical tensile strengths distribution, and although it is somewhat different than existing statistical functions, it is similar to the normal distribution.

It is shown that the entire analysis of determination of the critical tensile strength is independent on the plate's thickness, although the latter is important to determine the magnitude of the bending moment at failure and the magnitude of the applied load that causes that failure. The model is found to be in close agreement with test data; it may explain the inspected and measured results and provide insight to glass plate behavior.

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1. Introduction

1.1. General

This paper deals with flat thin glass plates that are made of soda lime silica annealed glass. Such plates are commonly used in buildings windows glazing. In that implementation a thin rectangular glass plate is considered, however in the general case it may have any shape and size, it may be implemented in different applications and be subjected to different conditions. This paper focuses on the static behavior of rectangular glass plates with given boundary conditions that are subjected to a static short term loading system.

Although glass production is known for many centuries, its quality has been considerably improved over the last decades. Current glass technology allows production from well-defined raw materials [1], of large size, high quality flat glass panels with constant thickness. Commonly glass plates are produced within a thickness range of 2–25 mm. The production process and the typical properties are described in detail in the literature (e.g. [2]). Nowadays float glass is a common product of high quality and pronounced resistance. As such it may be used not only for architectural and functional needs but also may carry loads and serve as a structural element. Even in its most common usage in windows' panes it is exposed to loads, such as wind loads, thermal and other mechanical loads, and may also be exposed to vibratory, impact and blast loading. It is known that glass responds differently to different loading rates and durations [3,4].

There exist different methods for window glass analysis that are developed to address special cases of plate geometry, type of loading, etc., but none of them is free of pronounced shortcomings.

The existing models are based on experimental data; nevertheless they cannot consistently predict test results. Recent studies have criticized the existing models and their limitations with regards to glass plate design e.g. [5,6]. This reflects both the doubts

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http://dx.doi.org/10.1016/j.engstruct.2014.08.017
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and the lack of confidence with regard to existing methods and motivate for further investigation. It is already well known that glass panes of identical geometry that are loaded by the same loading system, break differently and the experimental ultimate load or stress varies within a wide range. In certain cases, bending test results provide scattered values of the bending strength with a spread of 30–50% of the mean strength [7]. In different tests the location of facture origin varies within a wide range and mostly does not fit the location of the maximum applied tensile stress.

The experimental statistical distribution of the fracture strength of these plates was compared with well-known statistical functions, like the Weibull, Normal or Log-normal distributions. In many cases e.g. [28] none of them represents properly the experimental results. Several methods for glass analysis e.g. [8] are based on the Weibull distribution, the parameters of which are calibrated from test results. However, calibration to different tests yields different parameters.

There is a need for a fresh look at the fundamental aspects of glass plate behaviour in general, and its failure under the action of static and dynamic loadings in particular. The present study has been initiated following some critical review of the current methods in an attempt to gain better insight of glass plate behaviour. It aims at proposing a new approach to predict the strength of glass plates that are subjected to static loading. The new approach is based on minimal assumptions without any calibration with test data, and is capable of demonstrating many inspected features of glass plate behaviour.

This paper aims at analyzing short term static loading on glass beams and plates at ambient conditions, as is commonly carried out in laboratory research and in standard tests. The lifetime behavior of a glass pane and the evolution of cracks with time as function of different loading and environmental conditions are beyond the scope of this paper and is a subject matter of future research.

The advantages of the proposed approach are its generality, the fact that it is based on the glass pane data and that it is independent on test results. It means that no calibration is required. The proposed model may yield the probability distribution of the tensile strength of glass as a result of the analysis and not as an a priori assumption, which is common to existing models. The present model is based on the geometrical and physical data of the glass plate including the flaw distribution and all the predicted results come out as results of the analysis. The present model sheds new light on several parameters that affect the behaviour of a glass plate and provides insight and tools to plan further for improved testing and better interpretation of test results. It may serve for further development to incorporate lifetime conditions and be further developed to provide a design tool.

1.2. Annealed glass

Annealed glass is characterized by its attractive properties: it is transparent and hard wearing; it has flat smooth surfaces and demonstrates a high compressive strength. These features, among others, make it an ideal material for windows glazing and for other architectural uses.

On the other hand, annealed glass is brittle and upon failure it breaks into sharp shards. It contains randomly distributed numerous flaws resulting mainly by its production and also due to cutting and handling. The flaws are very small in size and cannot be observed by the naked eye; however they significantly affect the material mechanical behaviour. In this paper we shall assume that independent on the density of flaws, the distance between flaws is sufficiently large compared to their size thus individual flaws do not affect each other, and the tested specimen fails when the first flaw reaches the fracture condition.

During its service life a glass plate is exposed to mechanical and thermal loads, as well as to water and different chemicals effects on its surfaces. As a result flaws' sizes may grow and new surface flaws may be developed. The accumulated effects continuously change the properties of a weathered glass plate compared to a new glass plate that has been just recently produced and cut for its planned usage. In order to study the glass product, independent of its lifetime history, we shall focus in this paper on new glass that has not been affected by all the above mentioned effects.

After annealing, the float glass is inspected to ensure that there are no defects larger than a few hundreds micrometers. Standards also dictate the maximum size of allowable flaws: for example, it is 0.2 mm according to European standards [9]. Any defected or broken glass may be recycled into the furnace.

Through the production line glass is cut into a typical size of 6.00 m × 3.21 m ("jumbo size") before being stored; this large jumbo size plate will be denoted herein as the basic plate.

1.3. Mechanical properties

At ambient temperatures glass is solid. It is characterized by its brittle behaviour.

The fracture toughness is about 0.75 MPa ($m^{0.5}$) [10]. According to EN 572-1 [1], the density at 18 °C is 2500 Kg/m^3, its Young's Modulus E is about 7 * 10^{10} Pa and its Poisson's ratio is 0.2.

The theoretical strength of plain soda lime glass, is almost 50% of its Young's modulus of elasticity, however glass plates usually fail at almost 3 orders of magnitude lower stresses [11,12]. This is due to the presence of flaws. The theory of facture mechanics may explain the observed strength levels.

1.4. Fracture of annealed glass

Glass is a brittle material that behaves as an elastic solid in fracture. Fracture of glass initiates at the location of a crack that first opens due to the stresses acting on it. This is the critical crack.

Due to the flaws distribution the critical crack is not necessarily located at the point of maximum tensile stress. Griffith [13] studied the failure of brittle materials and focused on glass as a representative material. He derived the well-known expression for the failure stress:

$$\sigma_G = \sqrt{\frac{2E\gamma}{\pi a}} \tag{1}$$

where σ_G – is the failure stress; a – is half length of the crack; γ – is the fracture surface energy of glass

Irwin [14] modified Griffith's theory and introduced the *stress intensity factor* that represents the elastic stress intensity near crack tip. For mode I loading, K_I is determined from:

$$K_I = Y\sigma\sqrt{\pi a} \tag{2}$$

where Y is a geometrical factor depending on the flaw shape (e.g. 1.12 for a general surface crack [15], 0.713 for half penny shaped crack on a flexural element [16], 0.637 for an elliptical crack [17], etc.).

Failure occurs at a stage when the stress intensity factor reaches its critical value K_{Ic} (fracture toughness). The value of the fracture toughness for lime glass in literature varies within the range of (0.72–0.82) MPa $m^{0.5}$ and commonly a value of 0.75 MPa $m^{0.5}$ is used. Eq. (2) shows that the critical stress is inversely proportional to the square root of the flaw size.

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