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The statistical interpretation of the strength of float glass for structural applications

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HIGHLIGHTS

- A distinction needs to be made between tin- and air-side for float glass.
- Rough data from the coaxial-double ring test with overpressure need to be corrected.
- Test data suggest the presence of a lower limit for glass strength.
- The 2-parameter Weibull statistics cannot well interpret the strength of float glass.
- The 3-parameter Weibull statistics gives the best interpretation for the failure stress.

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ABSTRACT

The characteristic value of the strength of annealed float glass, to be used in structural calculations, is assessed by standards on the basis of a classical experimental campaign using the Coaxial Double Ring (CDR) test with additional overpressure. Experimental data were regressed according to the 2-parameter Weibull distribution, assuming that the induced state of stress is equibiaxial in practice. We show that, by splitting the data in two categories according to the surface under tensile stress (either the "tin" or the "air" side), a more accurate statistical interpretation can be obtained. Comparisons with the normal and log-normal distributions are made with the chi-square goodness-of-fit test. Moreover, we observe that the calibration curve suggested by the test standard is not precise, and that the stress state in the testing configuration is not equibiaxial. Therefore the rough data need to be further corrected and re-scaled to a common reference condition, according to a criterion of equal failure probability, by determining the *effective area* of the loaded specimen. Doing so, the considered statical distribution are able to fit to the data with much more accuracy. Considering that for very low failure-probabilities the tails of the statistics are the most important, and observing that the 2-parameters Weibull function fails to interpret a lower bound for the strength of glass that can be inferred from experiments, the use of a 3-parameter Weibull distribution is proposed. After having derived the corresponding expressions for the effective area, we present a new statistical characterization of glass strength that provides the best fit with the experimental data, at least for the air-side.

1. Introduction

In recent years the research of high degrees of transparency has become a priority in architecture so to increase the use of glass in buildings. The role of this material has changed, passing from being used for simple infill panes, to constitute complete load bearing structures. Hence the necessity to improve our understanding of the glass capacity, in order to accurately determine the material strength and meet the design requirements [1]. However, some peculiar aspects, which are of minor importance for other traditional building materials, influence the mechanical properties of glass and render the determination of its intrinsic strength not straightforward.

Glass is a homogeneous and isotropic material, whose behavior is linear elastic up to failure, but the nature of its failure is brittle [2]. The macroscopic strength of glass is governed by microstructural flaws [3], whose unavoidable presence is due to the forming process and later handling. Even the cutting process of the specimens influences their mechanical response, because an additional defectiveness is generated at the borders that reduces the local

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tensile strength. The micro-cracks open in mode I when the stress reaches a critical limit, but they can grow over time even for stress values much lower than this [4]. This phenomenon, usually referred to as *static fatigue* or *slow crack propagation*, renders the macroscopic glass strength dependent upon time and is, indirectly, influenced by the thermo-hygrometric conditions [5] that, in turn, affect the speed of the slow crack propagation. Recognition of these effects is at the base of the micro-mechanically motivated models that are usually employed to interpret the macroscopic mechanical properties of glass [6].

Another essential aspect, not to be missed when evaluating the intrinsic glass strength, is that the larger the loaded surface, the higher is the probability of finding a micro-defect of critical size [7]. Thus, tests at a small-scale may cause the overestimation of the capacity of glass elements (size effect). Similarly, the material strength is influenced by the type of stress state: the uniform equibiaxial state is the most critical one, since it makes the direction of the maximum tensile stress always normal to the plane of the dominant crack (mode I opening) [8]. Therefore, in order to measure the *intrinsic* glass strength, a testing configuration should be used for which all the aforementioned phenomena, which are all sources of uncertainties, do not take a prominent role, if at all.

This is why the efforts were directed towards conceiving a test where an equibiaxial state of stress is achieved in the core portion of the specimen, sufficiently far from its borders. The Coaxial Double Ring (CDR) test prescribed by the standard EN 1288-2 [9], which is a part of [10], aims at this goal by prescribing to apply, simultaneously with the ring loading, an additional overpressure in the core area delimited by the inner ring. In this way, the geometric non-linear effects, which are the main cause of departure from equibiaxility, should be compensated. However, it has been shown in [11] that the calibration curve suggested by the standard is not accurate, and consequently the data have to be corrected according to a new curve, obtained from accurate FEM analysis. Moreover, the aforementioned test configuration, besides being hardly feasible, fails to produce the desired stress state within the specimen, and hence the corresponding results may be misleading if one does not correctly re-scale the data to take into account the actual state of stress.

The quantification of the departure from the equi-biaxiality conditions depends upon the statistical interpretation of the experimental data. The 2-parameter Weibull function is traditionally considered to be the best statistics to represent the distribution of micro-cracks, but in recent years many authors have been critically questioning about the validity of this assumption. Indeed, the *complete* Weibull distribution provides a third parameter, which represents a lower bound σ_0 for material strength. Traditionally, when the limit σ_0 is low and the type of failure is brittle, so that also the estimation of σ_0 is uncertain, it has been preferred to neglect such lower bound by assuming $\sigma_0 = 0$. In this way one obtains a 2-parameter Weibull distribution that is certainly on the safe side [12], while the *complete* 3-parameter form was maintained only for a few high-strength glass and ceramic materials [13]. However, Pisarenko and Poleshko [14] already in 1978 proposed the three-parameter Weibull distribution to characterize the strength of float glass, but this approach was later set aside probably because of the aforementioned reasons.

The statistical interpretation of brittle material strength and, in particular of glass strength, has been studied by many researchers. Most of them concluded that the 2-parameter Weibull model was not to be rejected, but some of them emphasized the fact that material strength does not seem to fall below a threshold level [15,16]. Of particular interest is a very recent contribution [17] directed towards the construction of Microelectromechanical Systems (MEMS) devices, where a generalized weakest link failure model was used to theoretically derive a 3-parameter Weibull statistics that fits exceptionally well the experimental data.

For the specific case of structural glass, whereas setting $\sigma_0 = 0$ can be considered acceptable when elaborating the data of an ideal test able to generate an equibiaxial stress state in the core of the glass specimen, this may lead to over-conservative estimates if one has to use the statistics to re-scale the test results towards the ideal equibiaxial reference configuration. Indeed, Przybilla et al. [18] proposed a method to re-scale data from three- and four-points bending tests according to a three-parameter Weibull statistical interpretation of glass strength.

During the 2000s, the working group CEN/TC129/WG8 of CEN (European Committee for Standardization) performed a very wide experimental campaign to define the characteristic strength of glass to be used in product standards, by considering hundreds of specimens from various manufactures. The experimental method was the CDR test with an additional overpressure described in EN1288-2 [9] and the corresponding data are recorded in [19]. To our knowledge, this represents the largest experimental campaign ever made for glass, but results were interpreted by assuming that the EN1288-2 test configuration produces an equibiaxial state of stress inside the inner loading ring. However, as already mentioned [11], the EN1288-2 test only partially achieves this ideal configuration and the calibration curve is not accurate, so that the correcting and re-scaling of the data appears to be necessary.

The aim of this article is twofold. On the one hand, we propose a better interpretation of the experimental data of [19] by correcting and re-scaling them according to the assumed statistical distribution. On the other hand, we compare different-in-type statistical distributions, in particular the Gaussian normal distribution, the log-normal, the 2-parameter and the 3-parameter Weibull distributions. The efficiency of the various approaches is evaluated according to the chi-square goodness of fit test. We demonstrate that the use of statistical distributions either than the 2-parameter Weibull's can lead to a better characterization of glass strength, that should be considered in a revision of the current product standards.

2. The experimental campaign of CEN/TC129/WG8

With the aim of obtaining consistent and realistic information on the bending strength of glass, the working group CEN/TC129/WG8 of CEN performed a wide experimental campaign with 741 failure stress measurements, whose results are recorded in [19]. Both tin-side and air-side surfaces[1] of the float glass were tested separately for each supplier and, in total, thirty samples of approximately 25, 6-mm-thick, plate specimens were tested with the set-up prescribed by the EN1288–2 standard [10]. The samples were obtained from eleven European glass manufacturing plants, a part of which was asked to produce repeat samples. By analyzing the failure stress values reported in [19], it is immediate to observe the high variation between the individual samples and, thus, to reach the first conclusion that 25 specimens are not enough to be representative of glass as a material for determining its allowable stress. This has been confirmed and reinforced by the not-negligible difference in repeat tests of the same glass from the same manufacturer.

2.1. The Coaxial Double Ring (CDR) test with overpressure

The EN1288-2 [9] standard prescribes a Coaxial Double Ring (CDR) test configuration, according to which large square specimens of side $l = 1000$ mm are loaded by two concentric rings of

[1] In the float process patented by Pilkington, glass is produced as a hot tape floating on a tin bath, hence the name *float glass*. There is the need to distinguish the face exposed to air (air-side) from the face in direct contact with the tin bath (tin-side), because they present a different-in-type defectiveness.