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Towards a new standardized configuration for the coaxial double test for float glass

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ABSTRACT

The macroscopic properties of float glass are governed by the opening of surface cracks in mode I. To bypass the influence of crack orientation and defectiveness of the borders (due to the cutting process), in the experimental measurement of the material strength the *panacea* would be to induce an equibiaxial state of stress in the core of the specimen. The Coaxial Double Ring (CDR) test achieves this ideal condition when geometric non-linearities are of minor importance. To compensate for second-order spurious components, ASTM C1499-09 indicates a CDR configuration with variable geometry according to the specimen thickness, whereas EN 1288-2 proposes the application of an additional overpressure. An analytic theoretical study of the non-linear effects in a CDR test is here presented. Assuming a Weibull statistical distribution of defects, for the CDR configuration with no overpressure, we obtain expressions in closed form for the effective area, a parameter that allows the re-scaling of the experimental data to a reference condition (equibiaxial stress on a unitary area) according to a criterion of equal failure probability. This method is used to propose a new standardized CDR testing method, with fixed geometry and no overpressure. Since the procedure of EN 1288-2 is proved to be ineffective because the induced stress state is not uniform and equibiaxial, a supplementary experimental campaign is reputed necessary, considering that the reference strength of glass in product standards has been determined with this testing method.

1. Introduction

The use of glass in buildings has been constantly increasing during the last decades as a consequence of the architectural research for high degrees of transparency. Especially in recent years the material has overcome its traditional role of simple infill-panels, to acquire a well-defined structural identity. This is indeed a new field of applications for this very old material, which is nowadays commonly employed for balustrades, load-bearing beams, floors, roofs, stairs and frames. Many researchers are engaged in improving the understanding of the structural glass capacity, in order to meet the requirements prescribed by standards in terms of safety and serviceability for structural members, but the reliability of any structural design is definitely based upon the capability of determining the material strength with the appropriate degree of accuracy.

Glass is the brittle material *par* excellence, hence the nature of its failure is catastrophic: unlaminated glass shatters violently once rupture at one point is achieved [1]. This is why this material is mainly used in composition with polymeric interlayers, which can provide the structural robustness in the post-glass-breakage phase [2]. The material is homogeneous and isotropic and its response is linear elastic up to failure, but there are peculiar aspects that characterize its mechanical properties. Indeed, the macroscopic strength of glass is governed by surface micro-cracks, which can open unboundedly in mode I once the positive crack opening stress reaches the critical limit. In addition, microscopic flaws can grow over time even when their size is far below the critical threshold [3], causing a delay in glass failure. This phenomenon, usually referred to as *static fatigue*, makes the glass strength influenced by the thermo-hygrometric conditions [3], which determine the subcritical crack speed.

Because of the sensitivity to the underlying defects, the macroscopic strength is affected not only by the maximum tensile stress, but also by the size of the specimen and by the ratio between the two principal components of surface stress [4]. If fact, the larger is the surface, the higher is the probability of finding a micro-defect of critical size [5]. On the other hand, since cracks open in mode I and they are in general randomly oriented, the probability that the plane of the dominant crack is orthogonal to the direction of maximum tensile stress decreases if, keeping fixed this value, the

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second principal stress diminishes. The orientation of the dominant crack is irrelevant only if the state of stress is equibiaxial. Since any reliable test procedure should be able to detect the characteristic size of the dominant defects in the specimen, ruling out any possible source of uncertainty, the current methods aim at achieving a homogeneous equibiaxial state of stress on specimens of standardized size.

Although some researchers have recently questioned about its applicability [6–8], the two-parameters Weibull function [9] is traditionally considered to be the best statistical approach to represent the distribution of the pre-existing flaws and to interpret the test results. Once the statistical distribution of the data is known from a standardized equibiaxially-stressed experimental configuration, with a micromechanically-motivated model [10] it is possible to derive the probability of failure for elements of different size, under any state of stress. This is done through a correction coefficient K, which defines the *effective area* of the stressed element (size effect) according to a condition of equal probability of failure [4].

In Europe, the standard EN 1288 [11] proposes four different types of tests to characterize the intrinsic glass strength under bending. The parts EN 1288-3 [12] and EN 1288-4 [13] standardize the classical four point bending (4 PB) test, but in this configuration the highest stress is at the plate edges,[1] where the defectiveness is different from the core because of the damage induced by the cutting process. This represents a source of uncertainty that should be avoided. The parts EN 1288-2 [14] and EN 1288-5 [15] propose two different Coaxial Double Ring (CDR) configurations, where the surface loads are applied through two concentring rings sufficiently far from the borders. The corresponding linear elastic solution predicts that the portion defined by the inner ring is under an equibiaxial state of stress but second order effects, which are the higher the thinner the specimen is with respect to its area, may disturb this ideal condition. To limit second-order effects, EN 1288-5 [15] indicates a very small diameter for the inner ring, of the order of a few millimeters, but the tested area is so small that the characterization of the gross surface defectiveness is uncertain [16]. The test provided by EN 1288-2 [14] is certainly the most sophisticated, because it considers large square plates of area 1 m^2 and prescribes an overpressure to act simultaneously with the ring loading, so to generate an *almost* equibiaxial state of stress in the core area delimited by the inner ring.

Pursuing the same goal of achieving an equibiaxial state of stress far from the borders by limiting the deflections, the standard ASTM C1499-09 [17], not specifically conceived for glass but for advanced ceramics, prescribes a Coaxial Double Ring test configuration with specimens and loading rings of various size, according to the plate thickness. Moreover, ASTM C1499-09 proposes corrections factors to calculate the effective area/volume, taking into account the contribution of that part of the specimen comprised between the two loading rings. The methods are calibrated for the case of advanced ceramics, whose elastic modulus may be much higher than that of glass, paying particular attention to the frictional forces that may be transmitted by the rings. This approach is consistent for sufficiently thick specimens, but when the plates are very thin the suggested diameter of the loading rings are so small that the configuration is similar to that of EN 1288-5 [15], with similar problems.

In order to clarify the various issues involved in the CDR tests, here a theoretical study is proposed that pays particular attentions to the effects of geometric non-linearities [18]. A good approximation for the non-linear elastic solution is obtained in closed form for the central core of the specimens. This allows to distinguish the *bending* stress from the *membrane* stress associated with second-order effects. The parameters that determine the analytic solution are just two, associated with the corresponding components of stress at the center of the plate. From the comparison with the linear elastic solution [19], which predicts that the state of stress in the inner ring region is uniform and equibiaxial [20,21], one can clearly recognize when geometric non linearities become of importance. The analytic estimates of the state of stress indicate that even a small variation of the radii of the rings can change the non-linear response.

The major importance of the analytic approach consists in the possibility of obtaining an expression in closed form for the effective area associated with the testing configuration. The effective area is strongly affected by the specimen size and by the Weibull parameters [7], but this dependence can be explicitly incorporated in one formula. This provides a synthetic view that is useful for the interpretation of the experimental data when the statistics, and consequently the Weibull parameters, are not known *a priori*, but must be derived from a best-fit interpolation of the test results, also accounting for the effects of the loading stress rates [22].

An example of application is proposed by referring to the results of an experimental campaign, recently performed in Italy [23]. The employed method was a CDR test without overpressure, in line with ASTM C1499 [17] but with fixed geometry [24,25]. In order to take into account that the state of stress is not equibiaxial, the experimental data need to be re-scaled to a common reference configuration by calculating the effective area, but to do this one has to know the Weibull parameters, which in turn must be determined by interpolating the re-scaled experimental data. The proposed expression for the effective area greatly facilitates this procedure, otherwise iterative, because it explicitly accounts for the statistical parameters.

Considering that during the float production process one side of glass paste is directly in contact with the molten tin bath (tin side), while the other surface is directly exposed to air (air side), different-in-kind surface defectiveness are present on the surfaces of glass. This is the reason why it is necessary to use two distinct Weibull distributions, in order to distinguish the cases in which the tensile stress acts either on the tin or on the air side. The Weibull modulus resulting from [23] was $m = 5.4$, for the air side, and $m = 7.3$, for the tin side. These are also the reference values that have been assumed in the Italian code [26]. Therefore, in the following we will refer to these value to illustrate the potentiality of the analytic approach.

The analytic results then facilitate the standardization of the aforementioned method as *the* testing procedure to determine the strength of annealed glass.[2] Motivation for this does not only derive from the purpose of eliminating the complication associated with the applied overpressure prescribed by EN 1288-2 [14],[3] but even more so from a critical analysis of EN 1288-2 itself. In fact, numerical experiments have demonstrated that the correlation proposed in [14] between the nominal gas pressure and the force transmitted by the actuator are far from being able to induce an equibiaxial state of stress in the specimen core. Indeed, the reliability of the results obtainable with EN 1288-2 [14] is a very important issue, because the reference values of the material strength recorded in product standards for glass have been obtained from the method therein described.

[1] With respect to the classical Navier's solution, the state of stress is even higher at the borders because of the width of the plate, whose lateral strain determined by Poisson's ratio is contrasted by the curvature induced by bending.

[2] The case of prestressed glass (heat/chemically strengthened or tempered) presents other difficulties [27] and will be the subject of a successive work.

[3] This type of test is very complicated and just a couple of testing machines that can apply the overpressure prescribed by [14] are available in the whole Europe.