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Critical issues in the design-by-testing of annealed glass components

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ABSTRACT

To assess the reliability of glass components, a common practice is to test full-scale prototypes in the lab, and verify that the failure load is higher than that predicted from the design strength by means of structural calculations. However, any procedure of design-by-testing should be considered with great care because the gross strength of glass, being governed by the opening of pre-existing cracks on the material surface, strongly depends upon the type of defectiveness, the specimen size, the load history and the type of stress field (uniaxial, bi-axial). A model based upon an assumed law of subcritical crack propagation and a distribution *à la* Weibull of pre-existing flaws is considered for the body strength of annealed glass. This allows to correlate the expected macroscopic strength of glass, measured from testing the prototype, with the target probability of failure, for any type of size and load history. The discussion of paradigmatic examples confirms that appropriate theoretical considerations are needed for the correct interpretation of the experimental results.

1. Introduction

The incessant investigation of ever greater transparency has led to an increasingly strong demand for glazed surfaces in modern construction works. Glass is being used in challenging elements, such as larger and larger panels, roofs, beams, floors, stairs and frames, where the brittle material is required to carry substantial loads, therefore achieving a definite "structural" role. Improvements in production and technologies, such as tempering, increase the macroscopic strength of this material. Lamination of glass plies sandwiching polymeric interlayers mitigates the effect of brittleness, because the shards remain adherent to polymeric interlayers after glass breakage. Considerable research [1–7] is being undertaken to improve the understanding of the load-carrying capacity of structural glass elements under the actions those elements are exposed to during their service life, in order to achieve the requirements in terms of safety and serviceability that are prescribed by construction standards.

The reliability of a structural design depends on the capability to determine the material failure strength with accuracy. At the macroscopic level, the most used methods to measure the mechanical strength of glass are the Four Point Bending (4BP) test and the Coaxial Double Ring (CDR) test, which are precisely defined by harmonized standards [8–10]. In general, the tests aim at inducing a uniform stress field in the loaded area of the specimen: the 4PB test [9] generates an almost uniaxial stress field,[1] while in the CDR test [8] the stress field is assumed to be approximately uniform and equi-biaxial[2] in the core of the specimens, so that edge effects have no influence. Results are often interpreted using a two-parameter Weibull distribution [13], which is traditionally considered the best statistical approach [14].

However, the strength of glass, the brittle material *par* excellence, is affected by some peculiar properties at the microscopic level, which are of minor importance in other building materials such as steel and concrete, but acquire a crucial role in this case. Glass does not exhibit any ductility and breaks as soon as the stress at a point overcomes a certain limit, but no theory of glass strength can disregards consideration of the underlying microstructure. In fact, the material strength is governed by the presence of existing microscopic surface flaws, which open and progress under the applied stress [15]. Therefore, Linear Elastic Fracture Mechanics (LEFM) is the most useful tool to investigate the mechanical property of glass and interpret its brittle character.

Surface treatments (especially along the edges) have a strong influence on the strength because they may alter the size and

[1] The stress field is in general not perfectly uniaxial, because a stress concentration occurs in proximity of the edges, where defectiveness is in generally greater that in the core of the specimen [11]. Therefore, the results may be strongly influenced by the type of edge working.

[2] A recent study [12] indicates that the state of stress in the test configuration defined in [8] is far from being uniform and equi-biaxial. Therefore, the validity of such a procedure will need to be questioned on a theoretical ground.

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distribution of surface flaws, and the larger the surface, the higher is the probability of finding critical defects (size effect). The state of stress is also important, because cracks open in mode I and the probability of finding a dominant crack at right angle to the maximal tensile stress is higher under an equi-biaxial state of stress than under a uniaxial state of stress. An even more peculiar aspect is that cracks can slowly grow in time without any variation of the applied macroscopic stress. This phenomenon, usually referred to as *slow crack propagation* or *static fatigue* [16], makes the glass strength strongly dependent upon the load history.

There are methods that allow to calibrate models based upon fracture mechanics, so to identify the main parameters by tests, computer simulations and the use of inverse analyses [17]. As a matter of fact, constitutive models frequently include parameters that cannot be directly measured in the laboratory, but need to be identified, e.g., by numerical simulations of tests and minimization of a properly-defined function, accounting for the discrepancy between measured and computed quantities. This is an inverse problem of material parameter identification that, in a statistical context, can be faced with the Kalman filter (KF) technique [18]. Recently, this rationale has been applied to determine the fracture properties of glass [19] through non destructive indentation tests.

In this paper, reference is made to the interpretation of results that can be obtained from *macroscopic* tests on large prototypes, starting from the assumption of a model of slow crack propagation [16] and Weibull statistics [14]. In general, it is well-known that also the results from standardized tests [8–11], where specimen size and load rate are prescribed, need to be re-scaled to take into account the size-effect and the influence of stress-type, before being interpreted statistically [20]. In other words, the characteristic value of strength must be referred to standard conditions, i.e., a particular specimen size (usually 1 square meter), a precise load rate (2 MPa *per* second) and a prescribed state of stress (equi-biaxial). When large prototypes with non-standard shape and various degree of complexity are tested, experimental data can be strongly affected by several factors, such as the surface treatments, the border finishing and the type of constraint. In any case, the values associated with a prescribed fractile of the population of data considerably change if the specimens size, the load rate and the type of stress field are different from those taken as reference.

Eurocode EN 1990:2002 Appendix D [21] provides general rules based on statistical methods to define characteristic values of the mechanical properties of a material/component by performing an experimental campaign. However, the population of data must be sufficiently large for a probabilistic characterization; where one test only (or very few tests) is (are) performed, no classical statistical interpretation is possible. Only the use of extensive prior information associated with hypotheses about the relative degrees of importance of this information and of the test results, make it possible to present an interpretation as statistical. Nevertheless, a common practice, used by many designers and also implemented in standards,[3] is to produce full-scale prototypes to be tested in laboratory to determine whether their actual response meets the design requirements deduced from the reference values of glass strength. Due to the costs of the prototypes, their number is necessarily low, and it is not rare to find structural calculations where the designers consider the results from testing of just one prototype.[4] In general, designers are happy if the prototype breaks at a stress level higher than the characteristic value of strength, usually associated with the 5% fractile value of the assumed distribution of material strengths deduced from standardized tests and considered as a reference quantity to be used in the design. Sometimes, designers strongly remark that the ultimate stress measured on the prototype is much higher than the characteristic value of glass strength prescribed by standards, arguing that such a value is too much on the safe side. However, some critical issues are neglected in this argument. First of all, the characteristic value of strength is in general associated with the 5% fractile of the population of data, whereas when testing just a few specimens one should expect, albeit tentatively, results closer to the median, i.e., the value corresponding to the 50% probability of failure. Moreover, the size of the prototype and the complex state of stress to which it is subjected should be properly taken into account. Finally, the loading rate during the experiments affects the results because of the static fatigue phenomenon.

The aim of this article is to show how all the aforementioned aspects can affect the result of experimental investigations. Given a distribution of strength *à la* Weibull for annealed glass, whose parameters have been calibrated[5] out of an extensive experimental campaign [11], and assumed a widely accepted model of slow-crack propagation [16], we consider the hypothetical testing of a reference structural component. For this, we theoretically calculate the values of strength associated with a target probability of failure, taking into account the size-effect and the type of stress, supposing that loads are either constant in time, or applied at a constant rate. Three paradigmatic examples are presented: (*i*) a plate under a uniform equi-biaxial stress field; (*ii*) a rectangular specimen in a four-point bending setup, chosen for the wide use that the 4PB test has in the practice to determine the flexural strength of beams and floors; (*iii*) an edge-supported plate under uniform distributed load, as the paradigmatic representation of a façade panel exposed to wind pressure. In all these cases, only the effects of the body stress are considered, although typical glass structures may also be stressed at connections or glass edges, which usually represent the weakest points. The interpretation of the edge-effects necessitates of an *ad hoc* statistics, but it will be not considered here. However, once the statistical distribution is known, the treatment is analogous.

For the considered cases, we will show that the failure loads associated with the 5% fractile and the median values for these different-in-type structures can be very different one-another, even assuming the same statistical distribution of strength for glass. Therefore, before designing an experimental test on a complex structure, it is always necessary, in line with the recommendations of [21], to preliminary estimate the consequences of size effect, state of stress, static fatigue, load rate, and define from this analysis the actual expectations in terms of structural strength for the required target probability. The method of analysis proposed in this article can take into account all these effects and, although applied here to three cases only, it can be extended to the most general configurations.

2. Probabilistic model of glass strength

The macroscopic mechanical properties of glass stem from its brittle nature, which is characterized by a high sensitivity to stress concentrations often caused by surface flaws. Accurate characterization of the fracture strength of glass must then incorporate the nature and response of such surface cracks, whose size and orientation are often unknown. Therefore, a probabilistic model needs to be used to statistically interpret the generally broadly dispersed experimental data.

[3] For example, the standards [22,23] regulate the testing of large façade panels.

[4] This observation is the result of the experience of one of the authors while serving as a reviewer of plans of glass construction works. Such an experience has been mainly made at the Board of Public Works at the Ministry of Infrastructure and Transport of the Italian Republic.

[5] The assessment of goodness of fit and confidence intervals according to the prescriptions of [24], to determine whether the measured data can actually be represented by means of one single Weibull function, is not the scope of this study. Here, we will consider the parameters that have been derived in [11].