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New calibration of partial material factors for the structural design of float glass. Comparison of bounded and unbounded statistics for glass strength

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HIGHLIGHTS

- Calibration of partial material factors depends upon the assumed statistics of glass strength.
- There is experimental evidence of a lower bound for the glass strength population.
- A truncated Weibull distribution can account for the lower bound for glass strength.
- Partial material factors calibrated from bounded statistics are much lower than for unbounded statistics.
- Coefficients to vary the class of consequences are in agreement with indication from EN1990.

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ABSTRACT

Partial material factors need to be calibrated to guarantee the target failure probability of glass structures according to the semi-probabilistic (level I) methods of design. Calibration is made by comparison with results obtainable with the full probabilistic approach (level III) on paradigmatic case studies. Considering the results of previous work that assessed the validity of various statistical models of glass strength, we use a generalized distribution of the Weibull type to derive new partial factors that account for a lower bound for glass strength or not. The partial factors so calculated are much lower than those previously obtained from the classical two-parameter Weibull distribution, and are in agreement with the coefficients commonly used in practice. Moreover, the variation of the partial factors with respect to changes in failure probability is similar to what is applied to other building materials.

1. Introduction

Glass is a very old material whose use in construction works has radically changed over the past few decades. It has evolved from a simple in-fill material for windows to an effective structural material of ever-increasing use to build roofs, floors, balustrades and stairs. There is the need to develop specific design methods to assure for glass structures safety levels comparable with those usually required for more traditional civil engineering construction works. Structural performance is typically defined by the maximum acceptable probability of collapse, as assigned by the relevant structural codes. In order to guarantee such performance, the semiprobabilistic method of design (level I) is usually employed: partial amplifying factors for the actions and partial reduction factors for the resistances are used, so as to ensure that the probability of failure is equal or lower than the target value. The partial factors for actions and materials are prescribed by structural codes on the basis of calibration from a full probabilistic approach and from practical experience. However, what are the correct material factors for glass is a matter of debate.

Glass presents many peculiarities with respect to other building materials. First of all, it is brittle. Its macroscopic strength is determined by the opening of small flaws on its surface whose shape is

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usually approximated as "thumbnail". Because there is no possibility of stress redistribution through plasticity-type phenomena, catastrophic failure of the whole glass structural component occurs when the opening mode Stress Intensity Factor (SIF) of the dominant crack reaches a critical value defined as the fracture toughness. However, it has been recognized that the cracks could extend even when the SIF is smaller than this critical limit, due to a phenomenon [1] referred to as *subcritical crack propagation*, or *static fatigue*. The susceptibility of glass to static fatigue must be taken into account in the design. The critical role played by a single crack is the reason why Weibull's weakest-link-in-the-chain concept [2] is universally accepted to interpret the variability of the measured strength of glass.

The strong dependence of the macroscopic response of glass on the existence of small flaws requires the consideration of aspects that are not as important for other building materials. One of these is structural size; the larger the loaded surface, the higher is the probability of finding a flaw associated with the critical combination of size and stress. The probability of failure is also dependent on the distribution of stress. For example, if the stress is uniform equi-biaxial the orientation of the cracks does not matter, but if the stress is uniaxial there is a lower probability that the surfaces of the dominant crack are perpendicular to the direction of the maximal tensile stress. And finally, the strength of glass is highly dependent on changes in the flaw population produced by the manufacturing process and subsequent handling. In the float production process, patented in the late 1950s by Sir Alastair Pilkington, a glass paste is poured on a bed of molten tin so to form a floating panel. The contact of the panel with tin, and with the successive contact with the rollers, can induce a higher level of surface damage on the "tin side" with respect to the "air-side". The cutting process may also cause additional damage and hence a local reduction of strength at the borders. All these aspects must be considered in the assessment of the expected probability of failure.

The failure probability that is considered acceptable depends on the consequence of the potential collapse and is prescribed by structural standards. This classification, indicated by the standard for the *entire* structure, should be detailed to the *single* structural element on the basis of the consequences of its own collapse. In Europe, the EN 1990 [3] indicates the accepted probability of failure for three Classes of Consequences (CC), varying from 1.335×10^{-5} for CC1, to 1.305×10^{-6} for CC2 and to 9.96×10^{-8} (CC3) in one year. By considering that the actions are the same for all structures, the required probability scenario is defined on basis of the glass resistance and the partial material factors γ_m. The complete probabilistic method (level III) directly measures the failure probability through the convolution of the cumulative probability for glass strength and the probability density function for the actions, and it is generally used for calibrating the γ_m. This is why the statistical model of material strength very strongly affects the values for the material partial factors. In particular, when such low failure probabilities are considered, a very accurate characterization of the left-hand-side tail of the population of the material strength becomes of primary importance.

The strength of glass is usually modeled using the traditional two-parameter Weibull (2PW) extreme value distribution. However, it cannot provide [4] an accurate description on the left-hand-side tail. Moreover, there are reasons in support of the existence of an intrinsic lower bound for the strength of commercial float glass [5]. A minimum strength value is attributed to rigorous factory production controls of visual transparency that concomitantly guarantee that the sizes of the surface defects remain well below an assigned value. While considering the capability of various types of generalized Weibull distributions in interpreting the experimental data, it has been shown [5], using the goodness of fit procedure, that "*bounded*" Weibull statistics, i.e., statistics assuming a lower-bound for population, are more accurate than "*unbounded*" statistics (especially for the air-side). One may be concerned with potential strength degradation from aging. It is true that natural abrasion/corrosion of the glass surfaces can increase the surface damage in glass. However there is substantial evidence that even the worst deterioration produced by sand blasting cannot push the strength of glass below a certain limit [5].

To our knowledge, all of the proposed design methods are based on the two-parameter Weibull distribution. Using this statistics, the probabilistic method of level III was applied for the verification of paradigmatic case studies [6], which served to calibrate the partial material factors γ_m to be used in the semi-probabilistic approach of level I. To distinguish the different classes of consequences, each one characterized by the target probability of collapse assigned by standard EN 1990 [3], a multiplication coefficient for the partial material factor was introduced instead of that for the partial factors of loads. However, the values of the γ_m so obtained are quite high, of the order of 2.55 for CC2 and 1.8 for CC1. In fact the values for CC3 were not even recorded because they were considered to be so high that they deserve further investigation. Note that the values were calibrated for small-size plates (of the order of 1 m^2), so that larger structures will be associated with even higher values. The values required by the two-parameter Weibull models, being so much higher than those traditionally used for the design of glass elements (which are based upon practical rules, construction tradition and professional experience), have been hardly accepted by the building industry.

This paper presents a new calibration of partial factors that relies on improved statistical distributions of glass strength. With respect to the paper by Badalassi et al. [6], the considered population of glass strengths derives from a much wider experimental campaign [7], obtained with a refined testing method [8]. The statistical model considered here is the "bounded" left-truncated Weibull (LTW) distribution that provides an excellent goodness of fit with experimental data, at least on the air side [5]. Because a lower limit for glass strength may be hard to accept, a comparison is made with the "unbounded" extended Weibull (EXW) distribution that, although not optimal [5], gives much better results than the 2PW. Both the LTW and EXW distributions are derived by the 2PW distribution and provide similar rescaling of glass strength to account for the effects of size and type of stress, with no major analytical complications. The new coefficients calibrated with the LTW distribution are substantially lower than those presented by Badalassi et al. [6] and are in agreement with the indications of practical experience. Moreover, the variation of the coefficients to pass from one class of consequences to another is much more limited and of the same order of magnitude of what is suggested in the EN 1990 [3] for other building materials. The results from the EXW distribution is intermediate between these and the calibration obtained with the 2PW statistics.

2. The statistical modeling of glass strength

We first provide a brief review of the experimental campaign used as the reference for the derivation of generalized Weibull distributions, capable of interpreting the left-hand-side tail of the population (at very low failure probabilities) better than the 2PW model, in addition to a discussion of possible effects on glass strength of aging due to natural abrasion/corrosion.

2.1. Experimental data

The experimental data used to calibrate the statistical parameters are those from the experimental campaign by the working