Construction and Building Materials 55 (2014) 114–127

Contents lists available at ScienceDirect

Construction and Building Materials

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

Safety factors for the structural design of glass

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HIGHLIGHTS

- Statistical approach to the structural design of glass has been pursued.
- Glass strength is governed by subcritical crack growth and Weibull statistics.
- Statistical distribution of wind, snow and anthropic actions have been considered.
- Verification methods of level I and III have been compared in paradigmatic examples.
- Partial safety factors of material strength have been calibrated for float glass.

ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form 4 January 2014
Accepted 6 January 2014
Available online 3 February 2014

Keywords:
Partial safety factors
Probabilistic method
Safety
Glass
Fracture mechanics
Brittle materials
Weibull statistic

ABSTRACT

The safety verification of glass structures is usually made on the basis of a deterministic approach, without assessing the underlying probability of collapse. In this article, we propose to use the semi- probabilistic method in the limit-state design of glass structures by presenting properly-calibrated values of the partial safety factors of material strength, so as to obtain a probability of failure compatible with the target values indicated for each class of consequence by Eurocode 1 (EN 1990).

Starting from a micromechanically-motivated model of fracture propagation, typically used for brittle materials, experimental results conducted in a previous campaign have been interpreted using the Weibull statistical distribution, taking into account that size-effect, type of stress (e.g., uniaxial vs. bi-axial) and the insidious phenomenon of subcritical crack growth (static fatigue due to fracture growth in time without increase of load) can affect the probability of failure. Actions like wind, snow and live (anthropic) loads have been modeled using the statistical distributions recommended in international structural codes. Then, the probabilistic method of level III has been applied for the verification of paradigmatic case studies, which have served to calibrate the partial safety factors to be used in the semi-probabilistic approach. A novelty, to our knowledge, is the proposal of a multiplication coefficient for the partial safety factor of material strength, instead that for the factors of loads, to distinguish in the verification the different classes of consequences, each one characterized by the probability threshold of collapse. The results of this study will furnish the basis for the design of glass structures according to the general performance requirements established by EN 1990.

1. Introduction

Glass is being more and more used with structural purpose as beams, plates or shells, to form columns, fins, walls, frames, façades, roofs [3]. Glass structures are rather expensive and potentially dangerous because of the intrinsic brittleness of the material, but quite surprisingly the current design practice still relies upon rules of thumb or personal experience, sometimes not corroborated by definite structural calculations. This is why there is an increasing effort, both at the national and international level, to define consistent structural codes especially conceived of for the design of glass, according to the same basic concepts and safety requirements commonly used for other structural materials (concrete, steel, timber).

However, glass presents specific peculiarities with respect to the other traditional building materials [4] because it is the brittle material *par* excellence. This renders its use in structural applications quite problematic since even a whatsoever small accident may produce catastrophic collapse. In fact, whereas steel or concrete have sufficient structural ductility to accommodate unusual loading distortions and strain concentrations, glass breaks

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http://dx.doi.org/10.1016/j.conbuildmat.2014.01.005

whenever the stress overcomes the limit value of strength at a point [31]. More precisely, failure of glass is associated with the progression of one dominant defect (crack), i.e., the one which undergoes the most severe combination of stress with respect to its intrinsic size (crack width and stress intensity factor) [33,36,34]. This is why the weakest-link model of failure, usually interpreted at the macroscopic level by a Weibull statistical distribution of material strength, is traditionally considered the most reliable [22,2,14].

Certainly, it would be desirable to use for the structural design of glass the semi-probabilistic (level I) method [12], but to do so it is of fundamental importance defining the partial safety-factors for material strength, which must be calibrated in order to achieve the target probability of collapse in the construction lifetime [26]. However, due to the aforementioned peculiarities, it would be meaningless to use for glass the same values employed for other building materials. Also the use of methods of level II should be questioned, because the values of the safety margin (β index) depends upon the specific probability distributions that are used to interpret the effects of actions and the material resistance: to our knowledge, no specific treatment exists for the Weibull distribution [26].

We are not aware of any existing technical recommendation for glass that coherently considers the probabilistic approach in the calibration of partial safety factors. Very recently, the CEN/TC129/WG8 has proposed the new EN16612[1] "Glass in building – Determination of the load resistance of glass panes by calculation and testing" [9], which claims to follow the semi-probabilistic method and the basics of design established in EN 1990 [12]. However, the partial safety factors of material strength proposed in EN16612 are not justified by a probabilistic calculation, or are just not recorded because their definition is left to the national annexes. There are many other national standards especially conceived of for non-structural applications of glass panes, but the calculation methods therein proposed are mainly based upon practical experience, experimentation and rules of thumb.

At the European level, the Regulation n. 305/2011[2], repealing Council Directive 89/106/ECC, has laid down harmonized conditions for the marketing of construction products, defining the basic requirements for construction works through seven categories. All *structural* products must comply with Basic Requirement n. 1 (BR1) – Mechanical resistance and stability – which is achieved following the structural Eurocodes. But existing standards for glass, including EN16612, deal with Basic Requirement n. 4 (BR4) – Safety and accessibility in use – which is different from BR1. Our personal opinion is that limited attention has been paid to mechanical strength and stability in existing regulations [23]. The works for a new Eurocode on structural glass that should address BR1 have just started, but a few years from now will be necessary for a preliminary draft. An attempt to fill, at least partially, the aforementioned gap has been made in Italy by the National Research Council with the document CNR-DT210 "Instructions for the design, construction and control of buildings with structural glass elements" [17], just approved.

The aim of this article is to present a proper calibration of partial safety factors for material strength to be used in the structural design of glass with the probabilistic method. This will be achieved by a comparison with the full probabilistic methods of level III [26] in some paradigmatic examples, considering wind, snow and live (anthropic) actions. Various aspects will necessitate of particular consideration, among which the statistical description of glass strength through a micromechanically motivated model based upon fracture mechanics. Other aspects of particular importance are the effects of edge finishing (seamed, polished or clean cut) and of surface treatments (enameling, serigraphy, coating). Moreover a peculiar phenomenon of glass, usually referred to as *static fatigue*, is that the application of long term loading can produce its rupture at stress levels far below the limit under short-duration actions. To account for this effect, reference has been made to a model for the static propagation of an equivalent dominant crack, which evolves in time according to a power-law dependence of the crack tip velocity upon the stress intensity factor. All these issues must be considered here from a statistical point of view. Glass strength will be interpreted through a probabilistic distribution *à là* Weibull, obtained from a previous, extended, experimental campaign [19].

The plan of the work is as follows. In Section 2, the basic concepts of the probabilistic approach are briefly recalled, with emphasis to the specific case of glass. The probabilistic model of glass strength used in the calculations is described in detail in Section 3. The procedure for the calibration of the partial safety factors for annealed-glass strength is presented in Section 4 and applied in Section 5, through comparisons with the full probabilistic approach of level III in paradigmatic case studies. Of course, the work is far from being exhaustive. Other important problems, such as the statistical characterization of the strength of pre-stressed glass (heat/chemically tempered), or the influence of edge finishing on glass strength, could not be considered here because an extensive experimental campaign is still missing. Issues that are still open are summarized in the final Section together with the concluding remarks.

We believe that the results of this study will furnish the basis for the design of glass structures according to the general performance requirements established by EN 1990 [12].

2. Probabilistic approach to the design of glass structures

In any kind of structural work, a certain level of stability and safety against failure is required. Such a level is assessed on a statistical basis, by defining the probability of collapse that is reputed acceptable as a function of the *consequences* of the collapse itself and the nominal lifetime of the construction. Although such an approach is well codified in the European regulation by EN 1990 [12], it must be detailed and extended to the specific case of glass, which present noteworthy peculiarities.

The standard EN 1990 defines three classes, referred to as CC1 and CC2 and CC3, according to the potential consequences of structural failure in economic, social, and environmental terms, including loss of human life. Each class is moreover associated with different categories of constructions based on their importance: for example, CC1 refers to agricultural buildings, CC2 to residential and office buildings, CC3 to grandstands and open buildings. Such classification, however, considers the structure in its entirety, in the sense that collapse is intended to imply loss of the entire construction.

Indeed, because of their cost, elements made of glass are widely used in valuable public buildings. On the other hand, glass structures often represent localized parts of the construction (façades, beams, parapets, staircases, etc.): their failure can certainly have very serious consequences, though hardly ever accompanied by collapse of the entire buildings. Their classification ought therefore to be based on the severity of the potential consequences due to *localized* failure of the element in question, without having necessarily to extend the higher consequence classes to all the glass elements making up the construction. If this was not done, the class

[1] This draft standard was initially called prEN13474 [8], but although having been under inquiry for more than ten years, it was never approved. Because of this, the proponents were forced to withdraw it. After having changed its name to prEN 16612, the procedure of public inquiry started again and the project norm was finally approved in 2013 and became EN 16612.

[2] Approved by the European Parliament on March 9th 2011.