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Structural integrity assessment of glass components in Concentrated Solar Power (CSP) systems

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ABSTRACT

Due to the importance of glass components in Concentrated Solar Power (CSP) systems, an integrated assessment procedure conceived to facilitate the design of an intrinsically brittle component, limiting the amount of calculations, is presented. Since the fracture strength of brittle materials depends on the size and distribution of flaws as well as the duration of loading, conventional design approaches are generally very conservative and large safety factors are often used. However, these large safety factors are somewhat arbitrary and not satisfactory, because it is not very clear what the true factor of safety really is. In this paper, it is firstly reviewed and discussed the advanced methods to characterise the strength of glass. Then, based on the Weibull statistical method and the resulting probabilistic theory of the weakest link, a new modelling framework is proposed to consider different possible failure mechanisms (overloading fracture and stress corrosion induced failure). In this way, the size effect as well as the multiaxial stress effect (including the contact stress between the glass component and the mount assembly) are considered. The integrated assessment procedure for structural glass elements is developed and implemented as a post-process of finite element analysis. The proposed procedure is demonstrated trough an application example: the design of a glass window to be used in a solar furnace reaction chamber.

1. Introduction

Glass materials are important functional materials for renewable energy technologies, such as solar photovoltaic (PV), Concentrated Solar Power (CSP), and energy storage [1]. For example, the glass windows in solar furnaces are key components for transmitting the solar radiation into the furnace and also keeping the desired pressure and ambient conditions inside the reaction chamber. Their fracture may lead to malfunction of the whole system. Therefore, the structural integrity and reliability of glass components are key issues for the operation and maintenance of the renewable energy systems.

The fracture strength of brittle materials, such as glass and ceramics, is dependent on the size and distribution of cracks or surface flaws [2]. Components stressed over a large volume (area) will activate a bigger number of flaws, and therefore have a higher likelihood of activating a critical large flaw (resulting in lower strength values). Due to high scatter in the strength data of glass materials, very large safety factors (up to 8 or more) are often used in glass component design. However, these large safety factors are somewhat arbitrary and not satisfactory, because it is not very clear what the true factor of safety really is.

In recent years, considerable research efforts have been paid to improve the understanding of the load-carrying behaviour of structural glass elements, and many new design approaches have been proposed based on the Weibull's statistical failure probability function [3] to improve the safety and serviceability of the structural glasses [4–8]. Porter [4] proposed the Crack Size Design method (CSD), and Haldimann [5] made further development to the solution of this problem with the Lifetime Prediction Model (LPM). Recently, Santarsiero and Froli [6] formulated a new semi-probabilistic failure prediction method, called "Design Crack Method" (DCM). Doyle and Kahan [7] and Sutherland [8] proposed more advanced method for glass strength forecasting which takes into account the probability of failure and the surface damaging level.

Based on the Weibull statistics and experimental data from testing silica glass rod specimens with diameters between 0.5 and 1 mm, a theoretical model was developed for estimating their fracture strength under different loading conditions [9,10]. By this method, the test results of strength from one testing type can be extrapolated to other test types, such as the uniaxial tension, three-point bending, and four-point bending. Besides, Rosa et al. [11] studied the subcritical crack growth in three engineering

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ceramics under biaxial conditions, and the results from the ring-on-ring tests were compared with four-point bending tests.

Moreover, it is still a major concern that the extrapolation from laboratory test results to components under service conditions. A number of effects have to be considered, such as the size effect, the stress gradient effect or notch effect, and multi-axial stress effect. In Ref. [12], the extension of the weakest-link model to multi-axial stress states was verified by comparing fracture stress distributions obtained in four-point bending and in a concentric ring-on-ring test; and, therein, it was discussed about how the selected failure criterion influences the predicted distribution of the fracture stress of a component.

Pietranico et al. [13] used the Weibull approach to model the brittle fracture of the ceramic substrates of electronic power devices. The brittle fracture of the ceramic layer can also occur from a material defect of the ceramic itself, such as a grain boundary, a micro-crack or a pore. These defects, being statistically distributed in the ceramic layer, cause the fracture strength to be also statistically distributed. A probabilistic approach is therefore employed as a fracture criterion.

It should be noted that Flaceliere and Morel [14] developed the probabilistic approach, even for metallic ductile materials, to model the volume and surface effects in high-cycle multi-axial fatigue. The weakest link theory coupled with a multi-axial endurance criterion, based on a micro-plasticity, was combined to take into account the effects of the stress gradient and the component size.

Mande [15] and Saung [16] systematically studied the glass window and seal design for concentrated solar receivers, to accommodate a spherical cap geometry that can withstand temperatures of up to 800 °C and pressure differential of 0.5 MPa (about 5 atm).

From the review of literature, it is shown that the mechanical behaviour of glass at breakage is very complex. More and more theoretical models, as well as experimental methods, have been developed. However, for engineering applications, the complexity of calculation procedures needs to be simplified reasonably. The motivation for this present work is to develop an integrated approach for analysing the crack problem of the glass components used in the CSP industry in order to incorporate the probabilistic modelling, the principles of fracture mechanics, and the details of the specific design in question.

In the literature, the weakest link theory [17] is widely applied for uniaxial stress state and single failure mechanism (brittle fracture). In the present paper, a new modelling framework is proposed to consider different possible failure mechanisms (over-loading fracture and stress-corrosion induced failure), to take into account the size effect, as well as the multi-axial stress effect (including the contact stress between the glass component and the mount assembly). Then, an integrated assessment procedure for structural glass elements is further developed based on the previous work of the authors [18]. The new modelling framework proposed in this paper is integrated into the calculation procedure based on fracture mechanics and the theory of probability. The objective is to conduct the probabilistic modelling of the complex behaviour of glass fracture, but to avoid the complexity for calculation in applications. The proposed integrated evaluation procedure is applied for one example: a glass window in a solar furnace reaction chamber, and then the results are discussed.

2. Mechanical characterization of glasses for strength forecasting

The two parameter Weibull distribution is the most commonly used mathematical representation of the relationship between applied stress and probability of failure for glasses [17]:

$$P_f = 1 - P_s = 1 - \exp[-(\sigma/\sigma_0)^m] \tag{1}$$

where σ is the applied stress; P_f is the corresponding probability of failure, P_s is the probability of survival; σ_0 is the characteristic strength (the scale parameter) representing the stress value at which $P_f = 1 - 1/e = 63.2\%$ (Euler's number $e \approx 2.71828$); and m is the Weibull modulus (the shape parameter) which is a measure of the amount of scatter in the distribution. Small values of m imply wide variations in strength, whereas large values of m imply more consistent strength values.

Theoretical models were developed by Moreira, Rosa et al. [9–11] for estimating the fracture strength of brittle materials (such as ceramics and glasses) under different loading conditions. For the materials with the fracture strength controlled by volume flaw, the probability of failure P_f in a stressed volume V can be calculated [14] as:

$$P_f = 1 - \exp\left[-\int_V (\sigma/\sigma_0)^m dV\right] \tag{2}$$

In many situations, the glass fracture strength is considered to be controlled by the surface flaw, therefore the probability of failure P_f can also be formulated [14] by the integral over the stressed area A as:

$$P_f = 1 - \exp\left[-\int_A (\sigma/\sigma_0)^m dA\right] \tag{3}$$

The effects of specimen size and stress state can be accounted for by rewriting Eqs. (2) and (3) using the effective stressed volume V_{eff} and effective stressed area A_{eff} , respectively:

$$P_f = 1 - \exp[-V_{eff}(\sigma_{\max}/\sigma_0)^m] \tag{4}$$

$$P_f = 1 - \exp\left[-A_{eff}\left(\frac{\sigma_{\max}}{\sigma_0}\right)^m\right] \tag{5}$$

where $\sigma_{\max}$ is the maximum stress in the body; V_{eff} is the effective volume; and A_{eff} is the effective area. Both are given by integrals with the stress σ as a function of position in the body [19]:

$$V_{eff} = \int_V (\sigma/\sigma_{\max})^m dV \tag{6}$$

$$A_{eff} = \int_A (\sigma/\sigma_{\max})^m dA \tag{7}$$

When the failure probability is expressed in terms of the effective volume or the effective area, the effects of specimen size and stress state are accounted for. They can be used to scale ceramic and glass strengths from any standard testing configuration to another, or from one loading state to another:

$$\frac{\sigma_{f1}}{\sigma_{f2}} = \left(\frac{V_{eff2}}{V_{eff1}}\right)^{1/m} \tag{8}$$

or

$$\frac{\sigma_{f1}}{\sigma_{f2}} = \left(\frac{A_{eff2}}{A_{eff1}}\right)^{1/m} \tag{9}$$

where σ_{f1} and σ_{f2} are the fracture strengths of specimens of type 1 and 2 (which may have different sizes and stress distributions); V_{eff1} and V_{eff2} are the effective volumes; A_{eff1} and A_{eff2} are the effective areas; and m is the Weibull modulus. Larger specimens or components are weaker, because of a bigger probability of containing larger and more critical flaws.

For general configurations and stress states, numerical methods are needed to be used for calculating the effective volume V_{eff} and the effective area A_{eff}. For some standardized specimen configurations and loading modes, analytical solutions were given in [20–23] and shown in the following examples: