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Verification formulae for structural glass under combined variable loads

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ABSTRACT

It is well known that, depending upon the thermo-hygrometric environment, surface flaws in glass can grow over time even when they are well below the critical size, eventually leading to failure of the stressed material. This phenomenon, usually referred to as *subcritical crack growth*, or *static fatigue*, implies that the macroscopic strength of glass depends upon the characteristic duration of the applied loads. Various criteria have been proposed to evaluate the effects of the simultaneous combinations of actions applied at different times of the load history. Here, starting from a consolidated model of subcritical crack growth, an analytical approach to this problem is presented. Safety domains are calculated and compared with the approaches prescribed by recent proposals for standards. The analysis of a few case studies confirms that some approaches are not on the safe side, whereas other approaches can be too conservative. A proposal for new verification formulae is presented.

1. Introduction

Recent architectural trends have favoured the development of new technologies that have brought considerable improvements in the use of glass in buildings. This material has become a real structural material, not any more confined to form the building envelope, but used to construct self-supporting roofs, floors, staircases, beams, pillars and frames. When the load bearing capacity becomes a basic requirement, it is customary to speak of "structural glass", even if this term may lead to ambiguities because the adjective "structural" refers to the application rather than to the material, which is nothing but the same commercial glass used elsewhere and not a special glass, *ad hoc* manufactured. Since glass has to safely withstand considerable loads, structural verifications have to be performed, but unlike other structural materials, whose properties are well-known so far, the design methods for structural glass are still the subject of studies. On-going research is redirecting them towards even more precise approaches.

The strength of glass, the brittle material *par* excellence, is in fact affected by some peculiar aspects that are not relevant for other structural materials, like steel and concrete. Certainly, glass does not exhibit any ductility at the macroscopic level, and breaks as soon as the stress at one point overcomes a certain limit. More precisely, failure of glass is governed by the existing microscopic surface flaws, which can open and progress under the applied stress [1]. Linear Elastic Fracture Mechanics (LEFM) is therefore the most useful tool to investigate the mechanical properties of glass and interpret its brittle behavior. In particular an intriguing phenomenon, common to most brittle solids and usually referred to as *slow crack propagation* or *static fatigue* [2], is that cracks can slowly grow in time even when the stress intensity factor is far below the critical limit. This produces the delayed rupture of the element when the applied macroscopic stress is constant, so that the macroscopic glass strength strongly depends upon the load history.

There are several models to evaluate the influence of the static fatigue phenomenon upon the strength of glass, among which one may cite the pioneering work of Brown [3] with his *load duration theory*. The *glass failure prediction model* by Beason and Morgan [4] is taken as the reference for standards in the United States [5] and Canada [6]. Models that interpret the subcritical crack growth with a LEFM approach are those proposed by Sedlacek [7], Fischer-Cripps and Collins [8], which have been adopted in Europe [9] and in Italy in particular [10].

At the practical design level, the semi-probabilistic approach prescribes to compare the stress induced by the design actions at the critical points with the design strength of glass, through the definition of appropriate partial safety factors [11]. Most standards [12,13,9,10,14] introduce in the expression of the design strength a "load duration factor" k_{mod}, which is a function of the characteristic duration of the action. However, during its lifetime the construction-work is subject to actions of various nature with different characteristic durations, which need to be combined to account for their

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