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Hazard maps and global probability as a way to transfer standard fracture results to reliable design of real components

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ABSTRACT

Design and lifetime prediction of structural and mechanical components require the assessment of the global probability of failure to be determined from stress and strain distributions obtained by FEM, as well as calculation of hazard maps in order to facilitate redesign and recognition of critical parts to be inspected regularly. The so-called generalized probabilistic local approach (GPLA), developed by the authors, allows the primary failure cumulative distribution function (PFCDF) owning to a certain failure type to be determined for a given material from experimental data and used subsequently for probabilistic design. The approach ensures a realistic safety margin provided that the failure criterion represented by an adequate generalized parameter (GP) and the corresponding failure criterion is properly recognized as a reference variable to be considered in the failure assessment. The way in which the results of such a reliability analysis are interpreted encompasses a variety of concepts under which failure can be understood and may be classified as global probability of failure and hazard maps, the former providing the conclusive failure probability for definitive design, and the latter representing, presumably, a risk of local failure that facilitates the possible component redesign but without providing the global probability of failure. In order to promote the implementation of the methodology proposed, an application is exemplary presented for the particular case of experimental results of glass plates. A finite element subroutine is developed for calculation of hazard maps and global probabilities of failure.

1. Introduction and motivation

Currently, finite element calculations are often performed during the design stage of industrial components in order to guarantee a safe dimensioning, which can be based on a local failure criterion applied to each element of the finite element mesh. Sometimes, the safety factor of the component is defined as the relationship between the maximum stress that the component is able to withstand and the applied stress. However, such a procedure does not provide any information related to probability of failure, either locally or globally thus making difficult to take decisions concerning safety, redesign and maintenance.

Such a deterministic approach applied in the design phase is at odds with the experimental results carried out in the laboratory, which in general evidence considerable scatter. In this study, a twofold objective is pursued: first, to define a cumulative distribution function representing the scatter of the experimental data to be subsequently used for safe design of components, second, to transform maps of stresses or strains obtained by a finite element calculation into failure probability maps aiming at a safe design.

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A first step consists in adopting a failure criterion. Contrary to a probabilistic approach for which the suitability of the failure criterion can be checked by comparing the theoretically failure predicted distribution of the critical parameter and the experimental one found for the component, this is difficult, if not impossible, when applying a deterministic approach. This is due to the varying distribution of the critical parameter on the component and the statistical influence of size and shape on it. In this paper, a methodology is proposed aiming at overcoming all these limitations.

This paper is organized as follows: first, the concepts of hazard maps and global probability are introduced; thereafter, a validation of the failure criterion based on the GPLA is presented; then an application of the proposed methodologies is illustrated by practical examples related to structural glass; finally the main conclusions drawn from this work are summarized. As in Appendix A, a plug-in for the commercial software ABAQUS is developed to facilitate the calculation of hazard maps and the global probabilities of failure for components.

2. Hazard maps and global probability

The calculation of *global probability* and *hazard maps* is based on the so-called generalized probabilistic local approach (GPLA) developed by the authors in previous works [1–4], which as an extension of the local model of Beremin et al. [5], and that of Barredo et al. [6] allows a direct relationship to be found between the critical reference variable, as defined by the fracture criterion, and the failure probability. This relationship, known as primary failure cumulative distribution function (PFCDF) can be expressed by means of a three parameter Weibull cumulative distribution function (CDF):

$$P_{fail} = 1 - exp\left[-\left(\frac{GP-\lambda}{\delta}\right)^{\beta}\right], \tag{1}$$

where λ, β and δ are, respectively, the location parameter or threshold stress below which no fracture occurs, the shape parameter and the scale parameter associated with the selected reference area S_{ref}. The size effect of the specimen or component on the failure can be taken into account by simply adopting the suitable scale parameter provided that the weakest link principle applies.

2.1. Hazard maps

A *hazard map* is a graph that highlights the areas being affected or becoming vulnerable to a certain type of failure, providing visual information on the probability that this phenomenon occurs at each particular point of the studied space. These types of maps are typically created for the analysis of natural disasters such as earthquakes, volcanoes, landslides, and tsunamis. Particularly, in structural design they are taken into account to describe the stress or strain state though, in general, they are not related to probability despite the relevant information they could provide in the phases of design and inspection.

While Eq. (1) allows the probability of failure to be obtained for an element size S_{ref} subjected to any constant level of the GP, the critical parameter distribution in real components is usually not uniform, so that it must be evaluated locally at each finite element. Assuming validity of the weakest link principle, it is possible to obtain the probability of failure at an element of small size ΔS for a certain GP level, simply, by including the size effect in the former equation as follows:

$$P_{fail,\Delta S} = 1 - exp\left[-\frac{S_{ref}}{\Delta S}\left(\frac{GP-\lambda}{\delta}\right)^{\beta}\right]. \tag{2}$$

Expression (2) can be applied with generality to obtain the global probability of failure when a general non-uniform distribution of the generalized parameter (GP) arises from a FE calculation. It suffices to adopt an element mesh with sufficiently small elements size so that the distribution of the GP over such elements may be assumed uniform. An averaged value of the GP ones at the integration points, may be used as the reference GP value for the element implied from which the element probability of failure is calculated. The global probability of failure of the component results as combination of the local probabilities.

2.2. Global probability

The global failure probability of a component implies the simultaneous consideration of all the local probabilities of achieving the critical condition of failure at any of the elements constituting the component. The following example may clarify the difference between the safety global probability and hazard maps: having a chain under tension the global probability would report the probability of failure of the chain as a whole while the hazard map would represent the probability of failure associated to any link independently of the rest of links. In the design phase, but also along the lifetime of the component, the hazard maps complement the information provided by the global probability calculation in the sense that while the latter informs whether the component fulfills the safety