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Statistical joint evaluation of fracture results from distinct experimental programs: An application to annealed glass

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ABSTRACT

In this work, the generalized local model (GLM), as a procedure to derive the Weibull primary failure cumulative distribution function (PFCDF) related to an adequate reference parameter is applied to predict failure of annealed glass specimens from two different experimental test types. The procedure allows a unique PFCDF, identified as a failure material characteristic, to be inferred irrespective from the test data being evaluated either for each single test type sample separately or for a unique sample pooled from both single samples as a whole, whereby the particular specimen features pertaining to the two samples concerning specimen shape and size are considered in the assessment. Nevertheless, higher reliability is ensured in the parameter estimation for the case of pooled evaluation as a result of the higher number of specimens being jointly evaluated. In this way, once a suitable generalized parameter is selected, failure of specimens or components may be reliably predicted independently of the specimen shape and size chosen for the tests. The quality of the generalized parameter selected can be also discerned using this methodology. The applicability of the approach proposed is demonstrated by a practical example comprising two different test types on glass plates.

1. Introduction and motivation

The main objective of experimental programs in fracture mechanics consists in inferring the critical value of a reference generalized parameter (GP) identified with failure of the material, such as an equivalent stress, stress intensity factor, J-integral, or any other one characterizing that critical condition. In any case, it is well known that the scatter of the critical reference parameter is omnipresent and must be evaluated statistically.

Aiming at achieving a more general overview of the parameter influence, experimental programs usually encompass distinct test batches or samples, each of them consisting in a low number of specimens of similar characteristics with certain parameter diversity (for instance, specimen shape and size or test type).

As a consequence of the relative specimen scarcity and sample diversity, the reliability of the statistical assessment of the failure phenomenon declines revealing a conflict of interest: from the point of view of achieving a reliable cumulative distribution function (cdf), a sample consisting in a large amount of similar tests is desirable but, on the other side, testing several sample classes, implying distinct shape, size and test type, would be ideal to confirm the universality and suitability of the generalized parameter though the latter implies the inherent inconvenience of their statistical assessment.

In previous works [1,2], the authors have introduced the so-called generalized local model (GLM) to derive the primary failure cumulative distribution function (PFCDF) for a generalized parameter based on experimental data even from specimens with different geometry and size. Accordingly, the primary cdf of the generalized parameter may be interpreted as a material property allowing failure of specimens or components to be predicted independently of the specimen shape and size and test type selected for the experimental program. Thus, a probabilistic failure prediction of components, when subjected to whatever, uniform or non-uniform, distribution of the generalized parameter can be accomplished.

In this paper, a methodology based on the GLM allows the primary failure cumulative distribution function of failure PFCDF of the material to be derived from a joint evaluation of the results obtained for the different samples as a whole. In this way, the joint PFCDF can be determined as a failure material characteristic pooling all the experimental results obtained from distinct test programs consisting in diversified samples concerning specimen shape, size and test type. In any case, the joint PFCDF allows the probability of failure for any of the samples to be predicted,

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Nomenclature

GLM	generalized local model	P_{int}	global probability
GP	generalized or reference parameter	λ	location Weibull parameter
PFCDF	primary failure cumulative distribution function	δ	scale Weibull parameter
EFCDF	experimental failure cumulative distribution function	β	shape Weibull parameter
P_{fail}	global probability of failure	S_{ref}	reference size
P_{sur}	global probability of survival	S_{eq}	equivalent size
$P_{sur,\Delta S}$	probability of survival for an elementary size ΔS	RoR	coaxial ring on ring test
$P_{fail,\Delta S}$	probability of failure for an elementary size ΔS	4PB	four point bending test

irrespective of the particular features of the specimen involved whereas more confident parameter estimation is achieved as a result of the higher total number of results implied in the assessment.

The applicability of the approach proposed is corroborated by a practical example, which provides satisfactory results. The results of a large experimental program in which annealed glass specimens of different dimensions based on four-point bending and coaxial double ring tests (also known as ring on ring test) are tested and evaluated by applying the generalized local method. Annealed glass is selected as a suitable material for the experimental program since, first, several test types, as 3- and 4-point bending and ring on ring tests, are currently used to characterize glass failure strength, second, a large scatter is exhibited by the experimental data, and third, no satisfactory explanation is found till now in what concerns the lack of agreement among the results ensuing from the different test types currently used, what evidences to be an open issue.

Up to now, there is a certain lack in the regulation of structural use of glass [3]. The current methodology for structural glass design is basically represented by different approaches. Both the American code [4] and the Australian code [5] refer to glass as a panel not intended mainly for structural use while in Europe there is no consensus for a Eurocode for glass.

In European glass design concepts, it is mostly assumed that all cracks are oriented perpendicularly to the first principal stress. There are also global safety factors to diminish the risk of material failure, which are usually introduced by reducing the breaking strength in experiments to an allowable design stress. This concept, as opposed to the limit states one using probabilistic criteria based on a fracture approach, entails some important drawbacks [6] evidencing that the definition of criteria of probabilistic structural glass failure is still an open issue. In this paper, a contribution to overcome this situation is pursued.

The reliability level provided by two different fracture parameters and the corresponding failure criteria for glass under bending load is checked by comparing the failure results obtained experimentally owning to one test type with those predicted for this test type using the experimental results of the other test type, and vice versa. Thereafter, the suitable failure criterion is selected and all results from both different experimental programs are fitted as a whole thus providing higher reliability for the PFCDF.

The main goal of this work consists in demonstrating the possibility of pooling results from different experimental programs to evaluate a reliable PFCDF and to check the quality of the reference parameter for failure prediction. It is also important to notice that the generalized parameter distribution does not need necessarily to be described analytically but can be determined by finite element computation under general loading conditions. As a result, it is suitable for components design rather than being restricted to the use for laboratory specimens.

2. Experimental results and selection of the generalized parameter

2.1. Material properties and experimental procedure

Annealed glass, characterized by brittle behaviour besides large scatter of the test results [7], is selected as the testing material for investigating the applicability of the statistical joint evaluation model. The unavoidable distribution of micro-cracks on the surface is the mainly reason of this scatter to be taken into account using the proposed probabilistic failure model.

The experimental program is subdivided in 2 batches, in the following denoted "samples", comprising different shape of the specimens tested and the loading conditions, namely: (a) four point bending test (4PB) and (b) ring on ring test (RoR). A total of 30 specimens per sample are cut off from the same glass plate in order to reduce the variability of the material properties during the fabrication process. The main dimensions and characteristics for both samples are found in Fig. 1. The Young modulus and the Poisson coefficient of the glass are E = 72 GPa and μ = 0.23 respectively. All test are performed according to the UNE-EN 1288-3:2000 and UNE-EN 1288-5:2000 standards [8,9].

The following data measurements are performed during the experimental program carried out in a MTS Bionix uniaxial 100KN test machine. Load and displacement are measured directly from the test machine whereas, strains in the middle point and under load points are obtained, using strain gauges. Additionally, local displacements on the surface between the load rollers are recorded, by means of the digital image correlation equipment ARAMIS GOM 5M [10].

Former data are the starting point to proceed to fit and evaluate the experimental failure cumulative distribution function (EFCDF) and to check the usefulness of the iterative method applied here.

2.2. Results and simulation

Tables A1 and A2 in Appendix A and Fig. 2 summarize the experimental results obtained in the laboratory for both samples. In order to define the critical stress and strain conditions at failure,

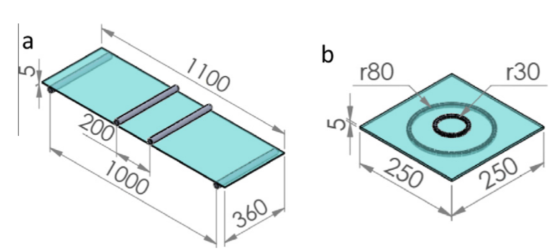

Fig. 1. Geometry of the specimens used (in mm): (a) 4-point bending tests; and (b) ring on ring tests.