Fragility curves as a handy forecasting method

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Abstract. The fragility curves method, which is commonly used in the prediction of damage associated with a certain earthquake intensity, is here extended as an agile and handy method, able to offer a reliable forecast of the evolution of deterioration process for masonry (or concrete) structures. We present some different contexts where the fragility curves provide a possible tool to be used in the planning of maintenance actions, by using parameters known in probabilistic terms such as the level of the damage and the time to achieve it. Remarkably, reliability of this method appears guaranteed even when the sample size of available experimental data is small, unlike other probabilistic methods based on applications of Monte Carlo simulations.

INTRODUCTION

The topic of assessing the useful life of new and existing structures involves a lot of uncertain parameters. Therefore, the modeling of structural performance evolution over time requires probabilistic approaches or simulation methods that are often expensive in terms of computational time and required resources. In the seismic field, many studies were devoted to the construction of fragility curves, which implicitly take into account frequency and depth of earthquake. Their use puts in evidence the link between damage and expected earthquake intensity, for different building typologies [1]. Here authors applied the fragility curves method to structural engineering problems. This forecasting method appears rather agile in application and is reliable even with samples characterized by a small number of data, though it is clear that a good sample distribution makes the method more powerful. The authors evaluate the goodness and the efficacy of the method, and then extend it to the prediction of some structural aspects that characterize the useful life of existing structures and infrastructures. Usually such aspects are not addressed by this type of approach and this is the novelty introduced by the paper. Here, after a brief theoretical treatment of fragility curves, we sum up results about three significant applications, with the aim of showing their efficacy even outside the seismic field. Therefore, presented results may be used to assess the quality of probabilistic estimations and to adopt best practice when developing new fragility functions.

FRAGILITY CURVES

Given a masonry (or concrete) structure, the deterioration process can be interpreted as a stochastic process function of time cycle τ and damage a, where a is a random variable (r.v.), because of experimental evidence. However, for a given time τ^* the deterioration process can be viewed as a function of the r.v. a only. To model this behaviour, a convenient density function must be chosen. The choice of the density must be based on knowledge of the modelled physical phenomenon and of the mathematical frame governing the behaviour of tails disribution. In [2] this subject was largely explained (Figure 1).

If the aim of the modelling is to predict the time needed to the system to reach and exceed those damage levels, or the stress needed to reach a given strain-rate and so on, then the deterioration process can be treated as a reliability problem. Indeed, reliability $R(t)$ concerns the performance of a system over time and it is defined as the probability that the system does not fail by time t. This definition can be extended by denoting with $\overline{R}(\tau)$ the probability that a system exceeds a given significant damage threshold by the time τ. The r.v. used to quantify reliability is $F_{\overline{T}}$, i.e., the

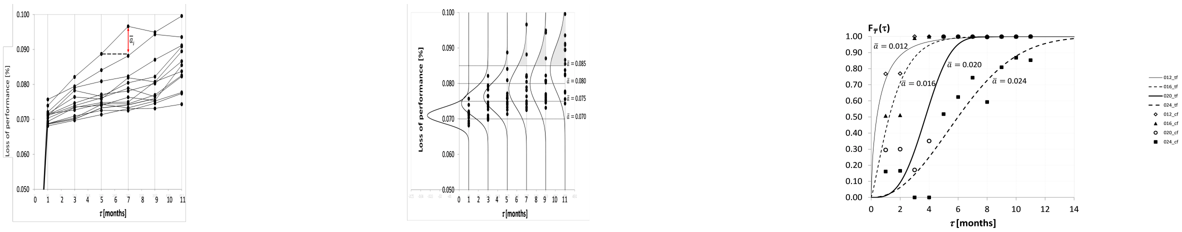

FIGURE 1. Loss of performance vs. time (left); modelling (middle); fragility curve examples, four different damage levels (right).

time in which the exceeding of the damage $\overline{a}$ can happen with a given level of probability. Thus, from this point of view, the reliability function is given by [3] (Equation 1).

$$\overline{R}(\tau) = \Pr(\overline{T} > \tau) = 1 - F_{\overline{T}}(\tau) \tag{1}$$

where $F_{\overline{T}}(\tau)$ is the distribution function for $\overline{T}$. Computing $F_{\overline{T}}(\tau)$ for different damage levels $\overline{a}$ allows for building the fragility curve for each $\overline{a}$ (Figure 1). A fragility curve describes the probability of reaching or exceeding $\overline{a}$ given damage over time (or another parameter). For a chosen damage level $\overline{a}$ at a given time τ^*, the probability to reach $\overline{a}$ is the area under the threshold $\overline{a}$ and the probability of exceeding it is the area over the threshold $\overline{a}$ (Figure 1-middle, grey area). Indeed, the computed areas over different thresholds $\overline{a}$ provide the experimental exceeding probability used to fit the fragility curves. Therefore, the exceeding probabilities evaluated for each damage level $\overline{a}$ at every time τ^*, allowed for creating the experimental fragility curves for each chosen $\overline{a}$ and their theoretical modelling $F_{\overline{T}}(\tau)$ with an opportune distribution function. In other words, the fragility curve defines the probability of a system to overcome a certain damage threshold $\overline{a}$ at a certain time $\overline{T}$, according to the specific damage process. This threshold may correspond to the thickness of the lost surface material due to salt decay, the strain-rate induced by the creep behavior, or other significant parameters.

SIGNIFICANT APPLICATIONS

In this section, to emphasize the importance of using fragility curves in fields other than the seismic engineering, three important applications developed by the authors will be summarized.

Application 1 - Durability assessment of construction materials in aggressive environment:

During their service life, the structures that are subjected to an aggressive environment may suffer degradation of their component materials, masonry included. The main attacks for masonry are the natural frost/defrost cycles. In presence of moisture and/or capillary rise these cycles can produce crystallization of water or salts inside the component materials (bricks or stones and mortar). As a consequence, the loss of surface material can happen. Along the time this decay can compromise the reliability of the structural element's cross-section. The typical decay is the delamination of the surface with the detachment of layers of stones or bricks and mortar.

To investigate the danger evolution of this phenomenon over time, the fragility curves were adopted.

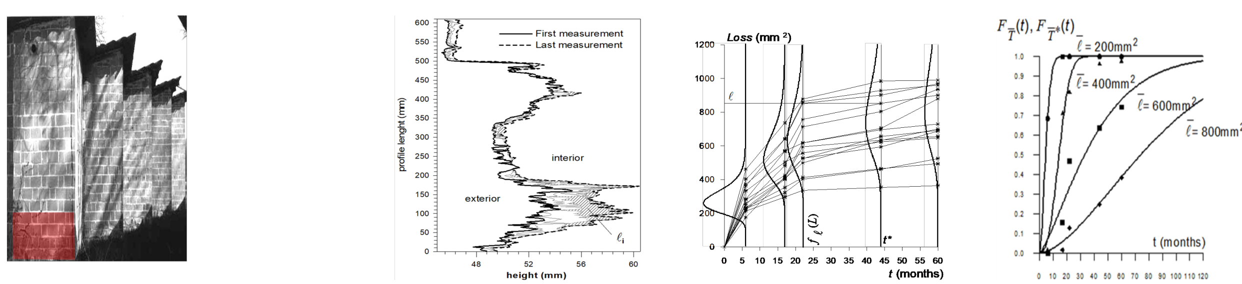

FIGURE 2. Full scale outdoor specimens (left); Measurements of material loss overtime after swelling has been removed (middle-left); Interpolation of the loss diagrams (*) and the modelling of the deterioration process L (middle-right); Fragility curves for different $\overline{\ell}$ (right).

The deterioration of the bottom surface of full-scale outdoor masonry specimens (Figure 2-left) subjected to salt crystallization due to capillary rise was measured though a laser device at different instant τ^* and along given profiles. The progressive loss of material was plotted in diagrams, were possible swelling was assumed like a damage and layers detached were removed (Figure 2-middle left). The damage parameter assumed to describe the progressive loss of surface material was the area, ℓ_i included between two consecutive diagrams. This area was automatically calculated by the computer code studied to eliminate swelling [4]. The instant τ^* considered were τ^* =6, 17, 22, 44, 60 months, in Figure 2-middle right, for each profile i, the plot of the damage ℓ_i versus time is reported. For each τ^* the loss recorded was modelled with an opportune probability density function (p.d.f.) $f_\ell(L)$. In this case the distribution chosen was a lognormal p.d.f.. More details on this choice are reported in [3]. Reaching of given levels of deterioration compromises the aesthetics of the facades and, even if minimally the bearing capability of the wall, so interesting was to understand the time in which each deterioration level could be reached. The levels chosen were $\overline{\ell} = 200, 400, 600, 800\,\text{mm}^2$ and for each of these levels the experimental $F_{\overline{T}}(t)$ and theoretical $F_{\overline{T*}}(t)$ fragility curves were built (Figure 2-right). The distribution chosen to model the experimental fragility curves was a Weibull distribution [4]. In Figure 2-right the modelling seems in good accordance with the experimental fragility curves obtained by the data recorded. In this case the curves describe the probability to reach a given damage $\overline{\ell}$ in a given time τ^*. Therefore, once a certain level of damage has been established and the probability of occurrence has been defined as an acceptable risk, it is possible to plan the most appropriate moments in which to operate on the facade with preventive and targeted maintenance actions.

Application 2 - Forecasting of the long term behavior for masonry subjected to heavy permanent loads:
The creep behavior of masonry seems to be one of the factors that most influences the mechanical behavior of historical buildings. The progressive decrease of the mechanical properties of the wall appears to be caused by long-term heavy loads and to be the cause of many unexpected and sometimes inexplicable collapses such as that of Pavia bell tower, Italy, suddenly happened in 1989 (Figure 3-middle). The influence of time on the mechanical behavior of porous materials is also evident from the laboratory tests, both of monoaxial-triaxial compression at different loading speeds, and in the compression tests at constant vertical load, made on wallets obtained by the Pavia bell tower ruin. The phenomenon that occurs under constant load is interesting; indeed, for the masonry it is noted that, while maintaining the load always at the same level of intensity, an increase in deformation is recorded, which can be classified into three different phases defined as primary, secondary and tertiary creep, each of which is characterized by a different rate of deformation (Figure 3-right). As well known, masonry presents numerous uncertainties and the evaluation of reaching a certain level of deformation under a certain level of stress is difficult to predict from a deterministic point of view.
For this application, it will be useful and interesting to model in probabilistic terms these dangerous effects connected with the long-term behavior of the masonry due to permanent heavy loads. To investigate this topic, the fragility curves method was applied. By experimental evidence, the strain evolution connected with a given stress history of a viscous material like a historic masonry can be described through the parameters ε_v and ε_h defined as the vertical and horizontal strain-rate respectively taken on the linear branches of the strain versus time diagrams obtained at the constant applied stress level σ_v^*. Therefore, for each chosen stress level σ_v^* ($\sigma_v^* = 1.5, 1.6, 1.7, 1.8, 2.0, 2.2\,\text{N/mm}^2$) the densities $f_E(\varepsilon)$ modelling the random behavior of the stain rate ε_v and ε_h were built. The p.d.f. chosen was a Weibull distribution because it well interprets the behaviour of rare values of the random variables assumed. Following the approach introduced with the fragility curves, experimental and theoretical fragility curves, $F_{\overline{\sigma}}(\Sigma)$, were built for different level of strain rate $\overline{\varepsilon_v}$ and $\overline{\varepsilon_h}$. The modelling of the experimental fragility curves was made using Weibull distributions. In this case the fragility curves describe the probability to reach a given strain rate ad a certain level of stress imposed. In Figure 3- middle and left, the fragility curves for strain rate levels $\overline{\varepsilon_v}$ and $\overline{\varepsilon_h}$ are plotted. The model seems to appropriately interpret the experimental results also capturing the passage between visco-elastic and visco-plastic behaviour.

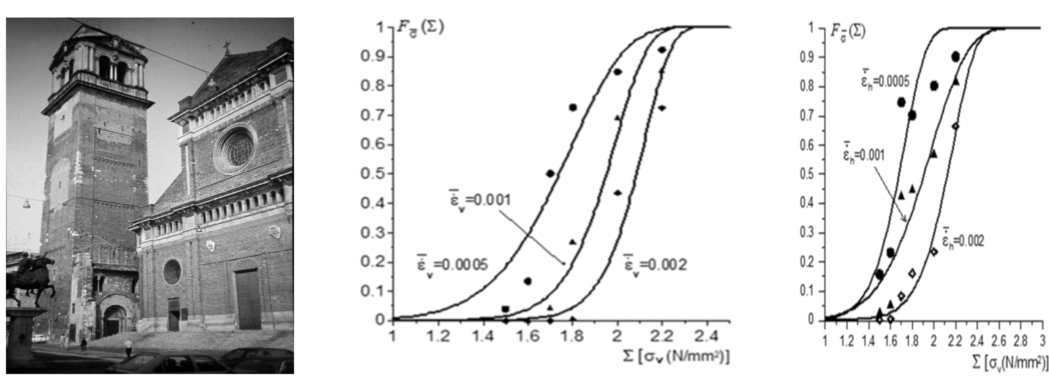

FIGURE 3. Civic tower of Pavia before failure (right); Experimental (symbols) and theoretical (line) fragility curves: vertical strain-rate (middle) and horizontal strain-rate (right).

Application 3 - The life-cycle assessment of deteriorating bridge structures:

For the third application, the authors apply the general concept of fragility curve to assess the decay of structures subject to deterioration. The authors want to generalize the fragility curve method by adapting it to the scope of building durability analyses. In this new context, the traumatic event for the structure is the natural deterioration of the structure, caused by the corrosion of the reinforcements. The example assumed is a reinforced concrete bridge affected by corrosion and material detachment. In this case the performance investigated was the bearing capability of a bridge deck.

To evaluate the loss of performance regarding the cross section of the bridge deck like significant parameters could be considered: the residual resistant sectional steel area, A_s, of the reinforcement and the variation of the relative ultimate bending moment M_z. According to the approach proposed with the fragility curves, the variation over time of the ultimate bending moment M_z was studied (Figure 4-left). Differently from the previous case, here the fragility curves were built using the areas under the thresholds; the reason is that the performance decreases over time, instead in the previous cases the loss increases (Figure 4-right). This approach showed the possibility to simulate different maintenance scenarios characterized by different intervals of action. The simulation puts in evidence both that fragility curves are reliable also in presence of a small data base and that they are able to suggest which levels of performance are best captured by shorter and which by longer maintenance intervals.

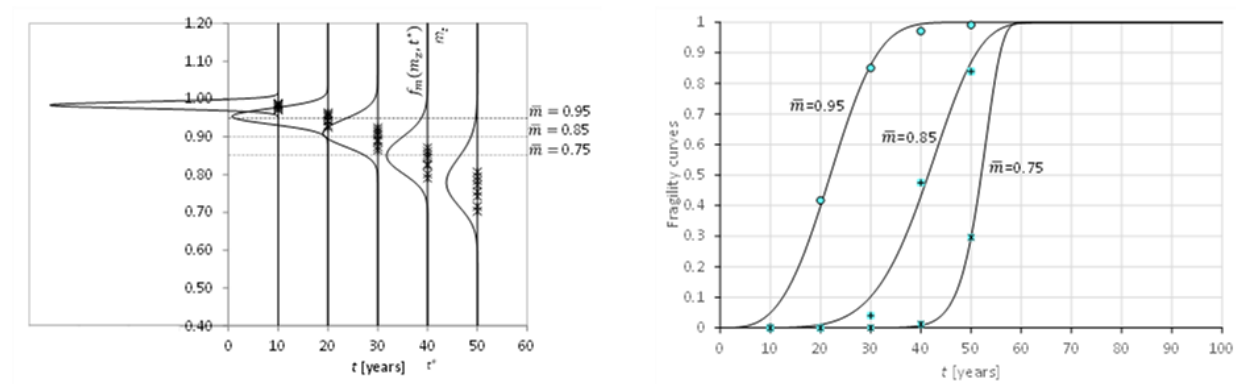

FIGURE 4. Probability of overcoming 3 most significant thresholds for the first 50 years of construction life (left); fragility curves relating to the probability of reaching each of the three residual ultimate bending moment levels considered (right).

CONCLUSIONS

The paper demonstrates that probabilistic approach based on the construction of fragility curves is a rather simple approach, which can be applied to different fields of investigation. Here the authors refer to structural engineering case studies. The simplicity of application allows the coding in easy-to-use calculation codes. Reliability of results is certainly affected by the sample size, nevertheless results seem to be reliable even with low sample size.

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