ASSESSMENT OF EXPERIMENTAL SEISMIC RESPONSE THROUGH DAMAGE EVALUATION

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SUMMARY

The paper presents a contribution for the assessment of experimental results obtained in seismic tests of structures in a context of fragility analysis for earthquake risk assessment. A methodology is proposed to estimate the vulnerability of specimens tested for increasing excitations, compensating for the damage accumulation in one same specimen (as opposed to the very expensive alternative of testing virgin specimens for each level of excitation). The method provides the damage evolution in relation to a "corrected" seismic intensity derived from the energy-input concept. Furthermore the paper illustrates the use of Bayesian inference strategies to update the fragility of a given typology on the basis of the combination of prior knowledge with experimental evidence.

INTRODUCTION

The vulnerability assessment of structures is based on the evaluation of damage suffered for various levels of seismic intensity, through the well-known vulnerability functions. The evaluation of vulnerability and associated fragility has an essential role both for the evaluation of the earthquake risk and for the probabilistic assessment of seismic reliability. Eventhough for structures to be built these issues are somehow solved and covered by seismic regulation, the situation is quite different in respect to the seismic evaluation of existing structures.

The possibility of using experimental approaches for the evaluation of vulnerability functions would involve the seismic testing of several identical specimens subjected to different intensity excitations (e.g. at least 5 or 6 independent experiments) what is economically prohibitive. On the other hand, testing one same specimen has the drawback that, with the succession of tests, the specimen accumulates damage and its response may become quite different from the one of a virgin specimen subjected to the same level of excitation.

To counteract this effect, a methodology is suggested for assessing the vulnerability of a structure from the experimental results of seismic tests on one specimen, based on the identification of its structural properties along a series of tests with differently graded input excitations and on the conversion of the input excitations into an equivalent earthquake intensity through the use of the energy-input concept.

The estimate of experimental vulnerability functions is discussed and the application of the proposed methodology in experiments carried out at the LNEC/Lisbon shaking table and at the ELSA reaction wall of the European Commission in JRC/Ispra is presented in the paper. Furthermore, the paper illustrates the usefulness of the seismic testing of one specimen representative of a class of structures for which risk has to be evaluated or for which the probability of reaching pre-defined limit states has to be estimated. The use of a Bayesian inference scheme to estimate the posterior fragility of a class of structures on the basis of the prior knowledge and of the experimental evidence is illustrated.

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VULNERABILITY ASSESSMENT AND SEISMIC TESTING

Vulnerability assessment of structures

The importance of evaluating the vulnerability of structures is well known in the field of earthquake engineering. The concept of vulnerability is mostly related with the evaluation of earthquake risk [3, 4] or alternatively may be assessed within the domain of seismic reliability. In the framework of the seismic reliability theory, vulnerability functions are used either for the estimate of the probability of failure of a structure or of a class of structures [6], or as the basis for the evaluation of the safety levels for each limit state [9].

Earthquake risk is normally approached either through the evaluation of the average expected losses ratio to an element over a given period of time, or in a probabilistic basis in terms of the probability of loss or injury to element exceeding a given extent over a given period. The evaluation of total risk to any element involves a combination of all the possible levels of earthquake hazard, taken as the probability or average expected rate of experiencing earthquake ground motion for given levels of severity, with the vulnerability of the element. In this context, vulnerability is generally defined as the degree of loss or injury to a given element at risk resulting from the occurrence of an earthquake of a given severity. The measure of loss depends on the element at risk and may be expressed accordingly, as a ratio of numbers of persons killed or injured to total population, as a repair cost ratio, or as the degree of physical damage. In a large population of buildings, vulnerability may be considered in terms of the proportion of buildings experiencing some particular level of damage.

The consideration of the average vulnerability alone is not enough for an adequate loss assessment, as the distribution of losses within the set of elements at risk, such as buildings, is generally very wide, with some elements sustaining very high degrees of damage and others very little. The complete vulnerability has to be defined for a range of intensities corresponding to all possible events that may cause any loss or damage to the element at risk. Accordingly, the partial separate vulnerability distributions have to be assembled in a global vulnerability. For the elements where a degree of damage may be assessed, this vulnerability is generally expressed by means of damage probability matrices or damage probability distributions.

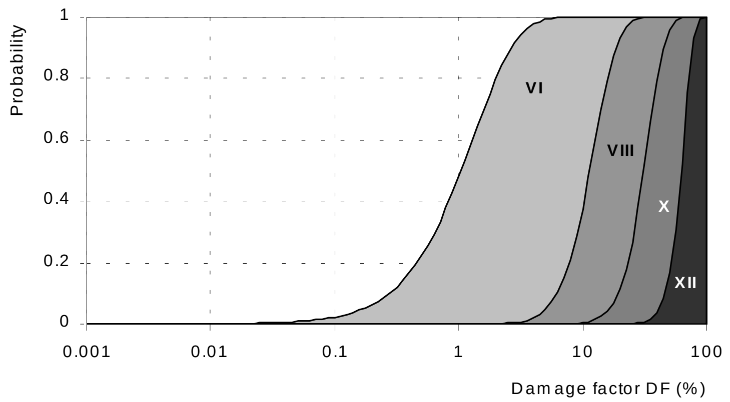

Figure 1: Fragility curves for low-rise non-ductile RC frames according to ATC13 (facility class 87).

These distributions are the so-called fragility curves that describe the non-exceedance probability of different damage states, for different values of seismic intensity. They may be expressed either for some pre-defined damage states as a function of intensity [4], or as a function of a damage factor (measure of economic losses) for discrete values of earthquake intensity [2]. These curves consider the variability and uncertainty associated both with the estimates of the response of the elements at risk for different intensities and with the damage states. Fragility curves for several typologies have been established, based either on the statistics of past earthquake damage or on expected performance of structures. Fragility curves based on expert opinion for low-rise non-ductile reinforced concrete buildings, are illustrated in figure 1, for seismic intensity IMM ranging from 6 to 12.

Seismic testing: damage evaluation and vulnerability assessment

The evaluation of damage has been approached both through analytical and experimental procedures. In what regards the quantification of local damage in structural elements, a wide range of both experimental data and analytical models has shown reasonable accuracy. However, a reliable method to estimate the global structural damage is still far from being available, in spite of the several existing methods for its evaluation, based either on the direct assessment of the global structural response, or on the weighting of local damage. Therefore, seismic tests on complete structures performed in large-scale experimental facilities may contribute to the solution of the problem, assuming that appropriate input motions and corresponding earthquake intensity are selected.

The analysis of experimental results obtained in seismic tests (shaking table and pseudo dynamic tests) performed on complete structures is far from being assessed in a consistent and quantitative way. In fact, until the present, these tests have been mostly used to evaluate the performance of analytical models developed to estimate the non-linear response of structures under severe earthquakes. The objectives of seismic tests on complete structures have to be fully clarified, in particular, if non-linear structural behaviour is expected. In fact, the calibration of local mechanical models, possible in cyclic tests of structural elements, is not the appropriate outcome of this type of tests, especially for hyperstatic structures where the measurement of internal forces is quite difficult. However, seismic tests are the unique way to evaluate directly the evolution of global structural damage, thus allowing both the calibration of the global damage models, and the realistic evaluation of the global damage limit states that a class of structures can undergo due to severe earthquake motions.

The importance of evaluating the evolution of global damage with earthquake intensity, expressed in terms of vulnerability functions, has been above focused and is particularly related with fragility analysis in the context of earthquake risk. However, the consistency of the outcome of seismic tests depends on two key aspects. First, the specimen to test should be selected in order to be representative of a given class of structures for which the risk is to be assessed. On the other hand, it is necessary to know the relation between structural damage and the economic damage variable considered in fragility analysis. While the first aspect is merely a question of defining a criterion for the selection of specimens, and consequently easy to solve, the problem of relating the structural damages with economic losses are far from being solved. In spite of some attempts to establish such a relationship in mathematical terms [1, 9] it is still necessary to invest significant efforts in order to obtain and calibrate such a relationship. Assuming that it is possible to establish the relation between global structural damage and losses, the output of a seismic test in terms of evolution of damage with intensity will correspond to a sample of the probabilistic vulnerability function of a given class of structures. Using probabilistic procedures, it will be thus possible to correct the estimate of the prior fragility associated with that class of structures.

Accordingly, the first main objective of a seismic test should be the identification of the vulnerability function of the tested structure corresponding to some pre-defined damage states (preferably including situations near collapse). The ultimate result should be the estimate of a posterior fragility combining the prior knowledge with the likelihood of the experimental occurrence, for instance through a Bayesian strategy procedure [7].

However, it may be stated that the evaluation of the vulnerability functions from seismic tests would only be possible if one test structure was available for each level of input motion, which is economically prohibitive. To overcome this problem a new parameter for earthquake intensity must be adopted. This parameter should be able to represent the main characteristics of earthquake-motion severity and translate the cumulative nature of the testing procedure. The assessment of experimental results recently obtained in LNEC and at the ELSA Laboratory in JRC/Ispra has indicated that the energy input appears to have the requirements above mentioned and can be used as the independent variable in the definition of an equivalent intensity to be considered for the evaluation of the experimental vulnerability function.

ESTIMATION OF EXPERIMENTAL VULNERABILITY FUNCTIONS

Seismic testing procedure

Assuming that the main objective of a seismic test should be the evaluation of the vulnerability function of the tested specimen, each experiment has to be naturally carried out in different test-phases corresponding to increasing intensities through the use of increasing input excitations. The methodology proposed herein is based on the identification of the structural properties of the model along a series of tests with increasing excitations and on its conversion into seismic intensity through the use of the energy-input concept. Such conversion allows a more realistic interpretation of the structural response as it accounts for the accumulation of damage.

The series of input signals to be imposed result from the consideration of real strong motion records of a given earthquake, or, which in this context may result even better, from the use of artificially generated motions consistent with a pre-defined hazard scenario. The initial signal of the set of increasing excitations corresponds to a given percentage of a nominal excitation for which a linear response is expected. In order to obtain the maximum information on the vulnerability of the model, the input signals should increase up to values inducing damage close to collapse of the specimen. This is generally possible in experiments and is clearly an advantage in relation to the numerical simulations that generally are not able to assess the situations near collapse. However, even if the test sequence ends far before major damage and only a few points of the vulnerability function are evaluated, the usefulness of this type of assessment is still significant, as it will be stressed later.

In order to assess the evolution of the response of the specimen along an experiment, it is necessary to adopt procedures for the identification of the dynamic properties of the structure. This has been done in LNEC shaking table identifying the structural properties on the basis of experimental transfer functions evaluated after each of a set of characterisation tests carried out alternately with the tests for increasing signals [5]. Another possibility is the use of time-domain identification methods for evaluating the continuous evolution of the dynamic properties of the specimen, as for instance has been successfully applied at the ELSA Laboratory in Ispra [8].

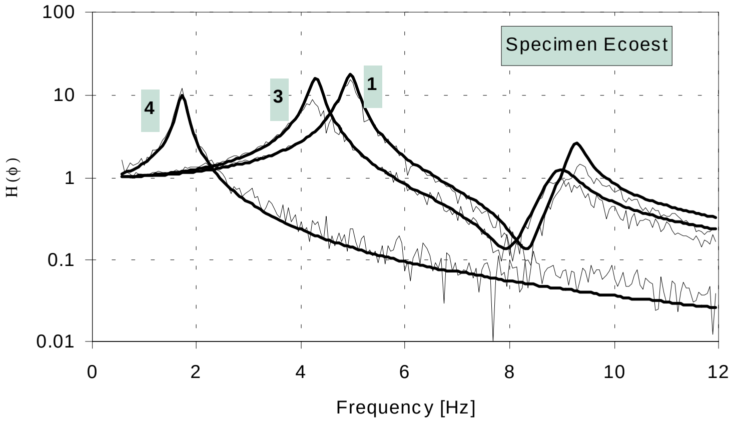

Figure 2: Experimental and analytical transfer functions for tests with increasing input signals

The evolution of the dynamic properties of the specimen give essential information on the evolution of the response, particularly in the case of models presenting an experimental response with appreciable degradation. It is the case of a set of reinforced concrete infilled frames which were tested within European project ECOEST II in LNEC shaking table [5] and suffered severe damage (reduction of natural frequency down to 35% of the initial value). For one of the models, the evolution of the transfer functions of the base acceleration to the top acceleration is illustrated in figure 2 for the direction along which the damage was more pronounced. These functions are presented in terms of amplitude for the first test (test-phase 1 with a reference PGA of 0.22g) and for the two of the last phases of the experiments (test-phases 3 and 4, both with reference PGA of 1.1g).

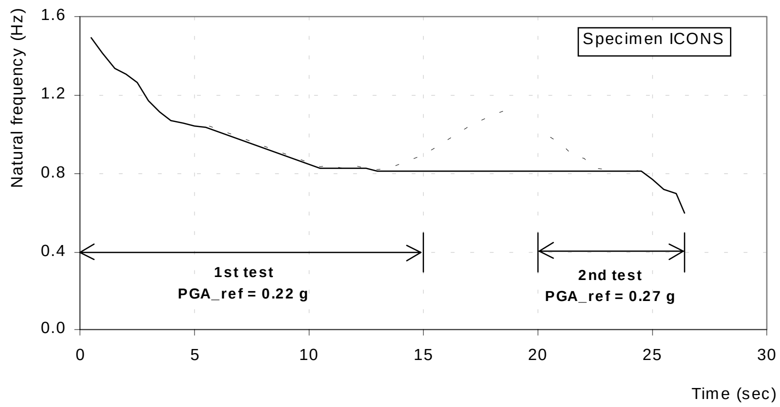

Figure 3: Time evolution of identified natural frequency for pseudo-dynamic tests of increasing severity.

Another example is illustrated in figure 3 that depicts the evolution of the first natural frequency of a 4-storey RC bare frame structure with no specific seismic design, tested within European ICONS project at the ELSA Laboratory, during two subsequent pseudo-dynamic tests. The structure was significantly damaged, particularly during the second test, with a reference value of PGA of 0.27g, attaining an interstorey drift of around 2.5% at the third floor. The identified natural frequency decreased down to 40% of the initial value, after the two tests.

The conversion of the sequence of tests in sesimic intensities is based on an equivalent energy-based peak ground acceleration *PGAen* for each test, evaluated from the nominal value of the earthquake excitation, *PGAnom*, and the energy input accumulated until test i, *Ei*, by the following expression:

$$PGA_{en,i} = \frac{E_i}{E_{nom}} .PGA_{nom} \tag{1}$$

To illustrate the application of this parameter, the evolution of the equivalent energy-based peak ground acceleration *PGAen* for the two cases referred above is presented in figure 4.

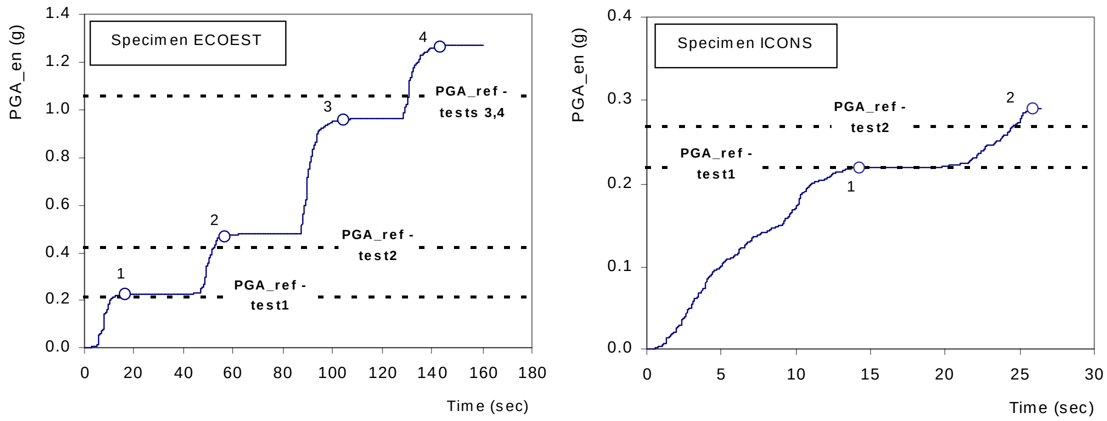

Figure 4: Evolution of equivalent PGA during tests with increasing signals within projects ECOEST II and ICONS.

The analysis of figure 4 suggests that the proposed energy-based peak ground acceleration appears to be a reasonable parameter for describing the input seismic intensity. In fact this parameter increases over the tests, as it was naturally expected as it reflects the accumulation of the energy input. The plain consideration of the reference values would not account for this effect, as it is clear in the case of subsequent tests performed for the same reference value of peak ground acceleration, for which the consideration of the accumulation of the energy input results in increasing values of the equivalent PGA.

Evaluation of the vulnerability

Assuming the reduction of the natural frequency as a good global structural damage indicator, it is possible to obtain the evolution of damage with seismic intensity, by combining the evolution of the identified frequency with the evolution of equivalent PGA along the tests. Moreover, if it is possible to relate the structural damage with losses, an experimental vulnerability for the specimen is obtained.

Figure 5 shows the experimental vulnerability obtained for the ICONS structure tested at ELSA, in terms of both structural damage and economic losses. Structural damage is expressed in terms of a damage index *d* given by:

$$d = 1 - \frac{f}{f_0} \tag{2}$$

where *f* and *f0* are respectively the current identified natural frequency at any phase of the experiment and the initial value of this frequency. The conversion of structural damage in losses was based on a best fit of a set of guess values established for the damage index *d* for given values of the damage factor *DF*. The procedure for establishing these guess values consisted on taking seven levels of qualitative damage, for which a value of the central damage factor is suggested in [2], and attributing to each of those levels a rational guess value for *d*.

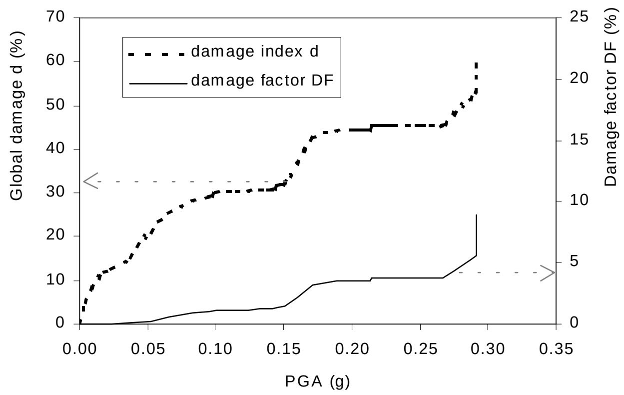

Figure 5: Experimental vulnerability function obtained for the ICONS structure.

Although the values of the damage index are significantly high (maximum value of around 61%), denoting that the structure suffered considerable degradation, the corresponding values for the damage factor appear to be quite low (maximum value of about 9%). This effect results from the fact that the economic losses reflect only partially the structural damage, as the structure is a small portion of the complete building (ranging from 1/4 to 1/3). On the other hand, the relationship between *d* and *DF* used in this study must be considered with relative criticism, as much work has still to be done in order to calibrate such a relationship, as above pointed out.

Assuming that the *d-DF* relationship herein considered is fairly reasonable for the aim of illustrating the methodology proposed, the experimental vulnerability function *DF-PGA* will be assumed as a sample of the probabilistic vulnerability function of a given class of structures. For this class of structures, which will be assumed to be the facility class 87 of ATC13 [2] (low-rise non-ductile RC frames), the posterior fragility curves may be estimated, as above referred, combining the prior knowledge (fragility curves presented in figure 1) with the likelihood of the experimental occurrence. For the case of the TMR/ICONS structure, the procedure is illustrated in the next section, using a Bayesian inference strategy.

USE OF BAYESIAN INFERENCE TO EVALUATE FRAGILITY

The development of fragility curves can be assessed by a Bayesian inference scheme. For that purpose it is necessary to establish a complete probabilistic model, which includes the definition of the probability distributions of the basic variables and of the parameters used to define those distributions.

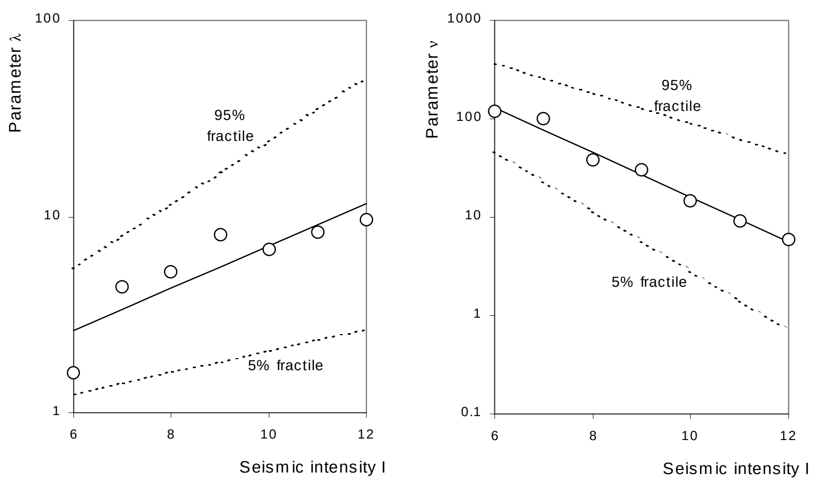

Figure 6: Variation of the parameters of the prior β distribution with seismic intensity *I* for low-rise non-ductile RC frames (facility class 87 of ATC13).

According to ATC13 [2] fragility curves for given values of seismic intensity *I* associated to a class of structures may be described by beta distributions $\beta I\ (D \mid \lambda, \nu)$ of the random variable *D* expressing the damage factor, characterised by the parameters λ and ν. In the context of this study, these are the prior distributions of the basic variable (damage factor), reflecting prior knowledge. The complete probabilistic model is established by expressing the parameters of the beta distribution as exponential functions of I in the form:

$$\lambda(I) = c_\lambda \cdot \exp(r_\lambda \cdot I) \qquad \nu(I) = c_\nu \cdot \exp(r_\nu \cdot I) \tag{3}$$

where c and r are the hyperparameters of the beta distribution. The hyperparameters c are considered constant and equal to the expected values of the parameters λ and ν obtained from the regression analysis of known statistical data, while r are assumed as random variables with normal distributions $\Phi r(\mu r,\sigma)$. These functions were established on the basis of the analysis of the ATC13 [2] expert opinion data.

For facility class 87 buildings, figure 6 depict the values of λ and ν obtained from the regression of known data for each value of seismic intensity considering prior beta distributions, confronted with the mean, 95% and 5% fractile of the functions $\lambda(I)$ and $\nu(I)$ obtained assuming respectively the values of 0.3 and 0.2 for the C.O.V. of the prior normal distributions $\Phi'(\mu r,\sigma)$ of the random hyperparameters r.

Using a Bayesian inference scheme, the posterior probability distribution $\Phi r''(\mu r,\sigma)$ of each random hyperparameter r is obtained by the expression:

$$\Phi_r''(\mu_r,\sigma) = \frac{\ell(\mathbf{D}|r) \cdot \Phi_r'(\mu_r,\sigma)}{\int \ell(\mathbf{D}|r) \cdot \Phi_r'(\mu_r,\sigma) \cdot dr} \tag{4}$$

where the likelihood $\ell(\mathbf{D}|r)$ stands for the probability of obtaining the sample vector $\mathbf{D}$ of experimental occurrences (for the given values of the seismic intensity I), for different values of the hyperparameter r:

$$\ell(r_\lambda|\mathbf{D},\bar{\nu}) = \prod_i \beta_I(D_i|\lambda(I),\bar{\nu}) \qquad \ell(r_\nu|\mathbf{D},\bar{\lambda}) = \prod_i \beta_I(D_i|\nu(I),\bar{\lambda}) \tag{5}$$

Assuming now that the posterior values of r are the expected values of $\Phi''(\mu r,\sigma)$, the beta distributions $\beta I\,(D|\lambda,\nu)$ which characterise the posterior fragility curves of the given class of structures are directly obtained. Figure 7 shows the result of the application of this strategy for the correction of the prior fragility of facility class 87 structures, on the basis of the seismic tests performed on the above referred ICONS structure.

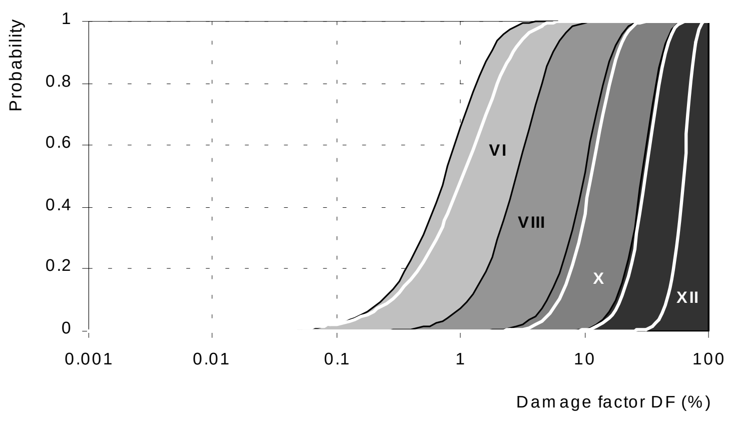

Figure 7: Prior (white) and posterior (area) fragility curves for low-rise non-ductile RC frames according to ATC13 (facility class 87).

Figure 7 shows that the prior information on the fragility of this class of structures was significantly modified. Infact, the likelihood of the damage experimental occurrences predominated over the assumed diffuse prior distributions (C.O.V of 0.3 and 0.2). Furthermore, the sampled intensities and associated values of the damage factor were relatively limited as they covered a narrow range of low seismic intensities. This gave rise to a smoother variation with intensity of the parameters of the posterior beta distributions, reflected in fragility curves by the width of the intervals between the distributions (narrower for low intensity and wider for high intensity).

The application illustrated should be thoughtfully interpreted as the experimental results used in the example were obtained in seismic tests whose main objective was not the estimate of the vulnerability, but rather the study of strengthening solutions. For this reason, the tests were kept within a limited range of intensities in order to assure that the structure would be repairable. On the other hand, the specimen is not fully representative of the typology studied, although as it was pointed out each of those typologies involves a significant variability.

CONCLUSIONS

The main achievement of the approach illustrated is the establishment of a consistent and complete two-step methodology for the assessment of seismic fragility of structures, on the basis of experimental results obtained with tests on complete structures, which in general terms evidences the usefulness of seismic testing as a contribution for policies of earthquake risk mitigation. The first step of the approach includes the evaluation of the experimental vulnerability of a specimen in terms of economic losses. Secondly, the obtained vulnerability is generalized as a sample of the probabilistic vulnerability of a given class of structures or typology, allowing the update of the prior fragility of that typology through probabilistic procedures based on Bayesian inference.

The efficient application of the methodology outlined requires however the solution of several key aspects, focused along the paper, which need further investigation in order to properly validate the assumptions. These include the selection of representative specimens, the adoption of a good parameter for expressing the seismic intensity of the experiments, the assessment of structural damage and its translation into economic losses through appropriate relationships, the availability of prior information on seismic fragility of structural typologies and the use of adequate probabilistic models for the update of the fragility of those typologies.

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