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Evolution of Damage on Historical Heritage Buildings in Presence of Catastrophic Events and Aggressive Natural Phenomena

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Abstract: The feasibility analysis of projects for the preservation of the historical heritage buildings is an important problem concerning the evaluation of "the total cost of intervention", which includes all the future damage costs. The total cost of intervention represents a suitable measure of the expected deterioration risk and its evolution obviously depends on the damage process which buildings are subjected to. That damage phenomena affecting masonry buildings pleased into an aggressive environment are suitably modelled by renewal processes: this happens both in the case of catastrophic events, or in the case of the so-called "natural aging", in which damage comes off gradually in time. In the hypothesis of a Markovian renewal process (Mrp) describing the damage process, the total cost of all the future damage is evaluated taking into account both the damage aspects: damages due to catastrophic aspects and damages due to aggressive environment, supposing different maintenance and/or rehabilitation scenarios. A semi-Markov process (s-Mp) is defined to model the damage rehabilitation history of buildings in presence of seismic events, natural ageing and rehabilitation strategies. The expected rewards connected to the process are defined; they represent a significant measure of the risk.

Key words: Historical heritage buildings, damaging phenomena, rehabilitation strategies, semi-Markov and renewal processes, expected rewards.

1. Introduction

In feasibility analysis of projects for the preservation of the historical heritage buildings, an important problem concerns the evaluation of the total cost of intervention, which includes all the future damage costs. The total cost of intervention represents a suitable measure of the expected deterioration risk and its evaluation obviously depends on the damaging phenomena which buildings are subjected to. Referring to masonry historical constructions, representing the most significant part of the Italian heritage buildings that has to be defended; authors showed [1] that damaging phenomena can be suitably modelled by Markov-renewal processes (Mrp). This modelling can be adopted both in the case of catastrophic events and in the case of the so-called natural ageing, in which damage comes off gradually in time.

In the hypothesis of a Mrp describing the damage process, in the two cases respectively, a semi-Markov process (s-Mp) is introduced to represent the whole damage process the buildings are subjected to. In order to carry out risk analyses, the total cost of all future damage is defined when different scenarios of maintenance and/or rehabilitation of the building heritage are supposed. With this aim a s-Mp is assumed to interpret the damage-rehabilitation history of buildings and a functional is introduced to represent the "total rewards" (costs and benefits) connected to the considered strategy. The problem, like this here proposed and formulated, allows identifying dynamic strategies of minimum cost [2].

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2. Damaging Phenomena in Mrp Hypothesis

The damaging phenomena hitting constructions are divided into two main groups: catastrophic phenomena composed by a succession of attacks carried out by the environment in a clear and identifiable time sequence, and the deterioration phenomena occurring in time gradually and considered, in their multiplicity, the cause of the so-called natural ageing.

In the both cases, the mathematical modelling of co-related deterioration processes which constructions are subjected to, can find valid solutions just in probabilistic field [3, 4]. The choice of the probabilistic model is problematic and doubtful; the first topic we should consider, when talking about the representation of different co-present and synergetic damage processes, concerns the possibility to use probabilistic models similar for guiding principles and mathematical structure.

For a long time the authors have proposed an approach to such issue using the typical structure of the environmental defence problems in which a system subjected to an aggressive environmental action, evolves in time modifying its own state; as a state a determined level of vulnerability of the system is intended [5]. This type of approach requires:

(1) the definition of the system state and of the environmental aggressiveness from which the system must be protected; it also requires the description of the future system scenarios, whether risk mitigation interventions have been carried out or not.

Significant uncertainties are implicit in the identification of the physical phenomena regulating the deterioration process, concerning both the environmental aggressiveness and the attacked system's behaviour. Nevertheless, it is possible to come to the formulation of reliable probabilistic models starting from cognition analyses based on two levels: taking into account both the information contained into the experimental data and the hypotheses that can reasonably be made about the involved phenomena's physics. The synergetic interactions between the two levels of knowledge allow an acceptable uncertainty margin definition.

Moreover, there are other topics to be considered with particular care:

(2) the definition of the system's deterioration state measure;

(3) the definition of the damage's occurrence time.

In presence of risk mitigation strategies, it is necessary to define evaluation criteria of their effectiveness.

Such issues are considered in the context of two particular phenomena:

- the damaging suffered by masonry constructions in a seismic area;
- the masonry deterioration due to salt crystallisation.

About the first phenomenon, studies concerning seismic hazard have been carried out in Italy at a national level [6]. These studies allow the formulation of suitable hypotheses about the nature of seismic events; the second one, both for the physical behaviours involved and the experimental methodologies of reading the phenomenon can suitably represent the numerous gradual deterioration phenomena of masonry characterised by material loss [7].

2.1 Masonry Buildings in Seismic Areas

The system is represented by the sample-building of the area; the process of seismic events in such area describes the environmental aggressiveness;

The system's state is defined by a unique parameter, the seismic vulnerability index *iv*;

The occurrence time of the damage coincides with the sequence of seismic events.

Consequently, the sample-building results subjected to a point process of state-transitions coinciding with the earthquake occurrence.

Deterioration model "A building's seismic vulnerability is represented by its behavioural character described through a cause-effect law in which the cause is the earthquake and the damage is the effect" [8]. This is the methodological frame we are referring to. The unique vulnerability index *iv* is introduced to measure the vulnerability. In order to measure the cause, the peak acceleration Y reached during the earthquake by the ground in a given side, can be assumed; in order to measure the effect, a unique damage index d is introduced, that is the damage endured by the building because of the earthquake acceleration Y, evaluated on the observation basis. The relation between Y and d depends on the building vulnerability defined by *iv*. In Fig. 1, a tri-linear type relation is represented, in which Y_I is the acceleration causing the initial damage and Y_C is the acceleration causing the collapsing of the building with vulnerability *iv;* Y^*, Y^{**}, ... denote increasing values of Y.

Survey identification cards are the most commonly used tools to perform vulnerability evaluation in Italy [9]. Through such cards *iv,* is defined as a linear combination $iv = \sum_i p_i w_i$ of parameters w_i referred to the typological, material and geometrical characteristics of building's structures, each one weighted by the weight p_i defined through the visual inspection of the building itself. Defined *iv* and the local Y from the relation shown in Fig. 1 the damage caused by an earthquake to a building sites in the area characterized by the local acceleration Y, can be expressed through a unique index d.

The values Y_I and Y_C defining the *iv*-building's behavior depend on *iv* according to experimental correlations [5] as shown in the Fig. 2.

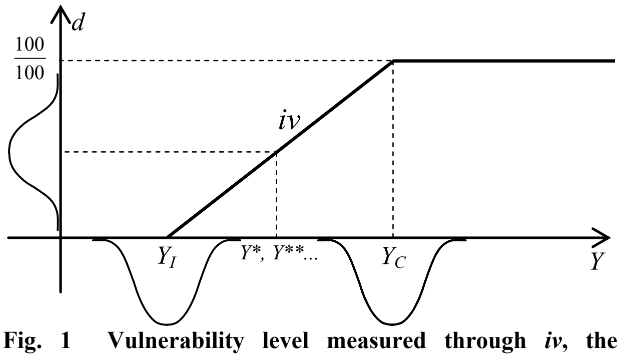


Fig. 1 Vulnerability level measured through *iv*, the vulnerability index of the sample-building.

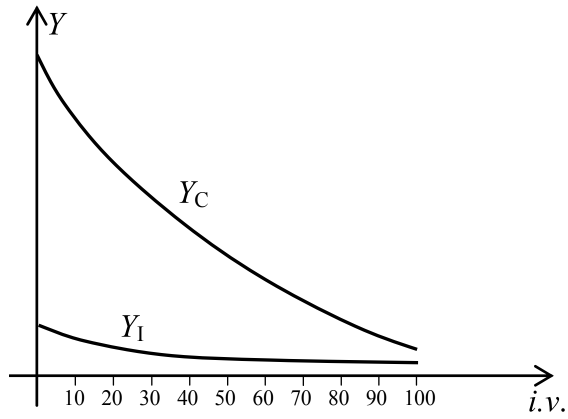


Fig. 2 Relations *iv* versus Y_I and *iv* versus Y_C: experimental relations deriving from sample earthquakes analyses.

From the methodological path described above the behavioural laws defining *iv*, with *iv* ranging between 0 and 100, are deduced (Fig. 3).

The definition of the damage process suffered by the sample-building depends on the hypothesis, generally accepted, that the earthquake's basic sequence might be reliable described by a Mrp [10-12].

The Mrp is defined by the two independent stochastic variables: τ_s , interoccurrence time between two successive earthquakes, and Y, local peak acceleration which can be developed by the earthquake, when it occurs. When the earthquake occurs and its effect are filled at site with acceleration Y the sample-building belonging to the class $iv = i$ goes from i to a more vulnerable class *iv-damaged*=i^*, i^{**}, ... The classes i^*, i^{**}, ... do not belong to the behavioural classes in Fig. 3; they can be defined by the cost of the damage repairing.

As a consequence, the sample-building's deterioration process results into a Mrp, or, in other words, into a sequence of transitions that coincides with earthquake occurrence: at every earthquake a transition between different states of vulnerability could happen and the building changes its vulnerability state, with transition probability p_{ii^*}, $p_{ii^{**}}$, ... (Fig. 4). In Italian seismic zones τ_s is suitably defined by mixture pdf f_{τ_s} of two distributions: exponential and Weibull [6].

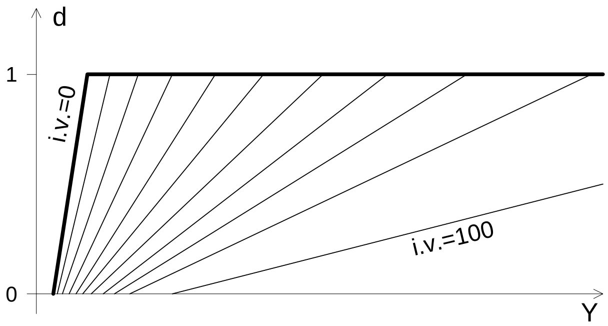


Fig. 3 Behaviour law defining *iv* of the sample-building.

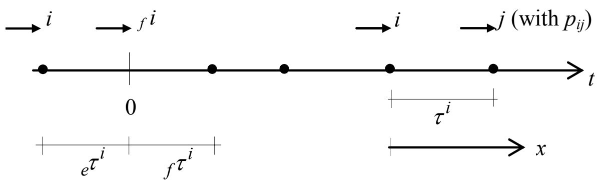


Fig. 4 The Mrp defining the damage process the sample-building is subjected to, because of: (1) the earthquake occurrence; in this case $\tau_1 = \tau_s$, ${}_f\tau_s$ depends on the elapsed time ${}_e\tau_s = t_0$ from the last earthquake; (2) the natural aging; in this case $\tau_i = \tau_n$, fτn depends on the elapsed time ${}_e\tau_n$. When the initial state i coincides with the undamaged state $\bar{i}$ the waiting time ${}_f\bar{\tau}$ differs from τn as it is shown in Fig. 5.

2.2 Masonry in a Saline Environment

It is very well known that high salt concentrations in an environment, associated to dry-wet and frost-thaw climate cycles, lead to a progressive deterioration of masonry materials. The most evident demonstration of the consequent damage is the surface delamination, considered as the loss of surface material which may lead, in time, to significant reductions of the resistant sections of the structural elements. The deterioration occurrence over time is, in this case, difficult to detect.

An experimental research on these phenomena [13], and on their modelling in probabilistic terms, has been going on for some time [1]. The experimental data, which the research is based on come from laboratory and in situ analyses carried out on masonry material samples and on wall panels of various dimensions and structures. In this case:

– the system is defined by the material sample or by the masonry panel sample; environmental aggressiveness is represented by the synergetic whole of phenomena helping crystallisation within the pores of the material and causing the material loss;

– the system's deterioration state is defined by the quantity of material lost;

– the damage realization time is not experimentally evident.

Deterioration model Two different considerations lead us hypothesizing that it is possible to introduce reliable stochastic models in which the deterioration process is carried out following a reasonable sequence of damage occurrence instants:

– about the nature of the physical mechanisms regulating the crystallisation phenomenon which is characterised by slow accumulation and instantaneous release of energy (though the crystallisation, the salt increases progressively its volume until it cracks the pores of materials in which it is laid);

– about the nature of the probabilistic models which provide to be reliable to represent the experimental data.

These models belong to the Mrp context [14]: they are based on the criterion of *failure,* namely, on the possibility to define a "characteristic damage", that is, the lost of a certain quantity of material, allowing us to identify the damaging process as a point process of *failures*, all the same, and alternated by the same interoccurrence time τ_n (Fig. 4). At every transition, the material sample belonging to state *i,* goes from *i* to the successive more deteriorated state $i+1$ with transition probability $p_{i,i+1} = 1$. The state $i+1$ can be included into the behavioural classes in Fig. 3.

We must now observe that the reliability of the Mrp hypothesis in the description of the data based on crystallisation trials performed in laboratory might seem predictable as the artificial reproduction of the aggressive environment; in this case it involves the activation of crystallisation cycles occurring in a regular succession of points of environmental attacks. But an experimental research carried out [13] on real scale models of stone or brick masonry and mortar into a natural saline environmental (the industrial suburbs of Milan) provided us similar result to the laboratory results. In this case, due to the high quality of data collected "in situ", due to their quantity and the long monitoring time, the research allowed to study the deterioration process as the Mrp of the stochastic variable, τ_n assumed to be the life time of the system in every state *i.* Since the initial state *i* coincides with the undeteriorated state $\bar{i}$ the first waiting time ${}_f\bar{\tau}$ differs from τ_n the Mrp can be defined a modified Mrp [10].

In Figs. 5, the compliance of the Mrp model with the experimental data is shown.

Finally, the Mrp hypothesis is a good choice for two reasons: it is restrictive and conservative in the prevision; it allows the formulation of suitable hypotheses on damage levels which aren't detected in the experimental trials.

3. Damage Process Connected with Environmental Aggression and Aging

The aim is to represent the damage process the buildings are subjected to taking into account both the seismic damage and the natural aging in order to evaluate possible synergic relationship between the two damaging phenomena. At first, the problem arise of introducing the same system state measure in the two cases; thus a research is proposed in order to individuate a connection between the amount of material lost, due to delamination, by the structural elements of the sample-building and the vulnerability index *iv* of the sample-building itself.

The deterioration of materials due to aggressive environments or ageing, can affect the performance of a structural system and its reliability over time; the modeling of this process requires a probabilistic approach that must be based on experimental datasets with significant population, usually not easily available. To build a suitable dataset a simulation approach is introduced on the basis of experimental results shown in section 2.2 and of the *iv* evaluation obtained through the survey cards mentioned in section 2.1.

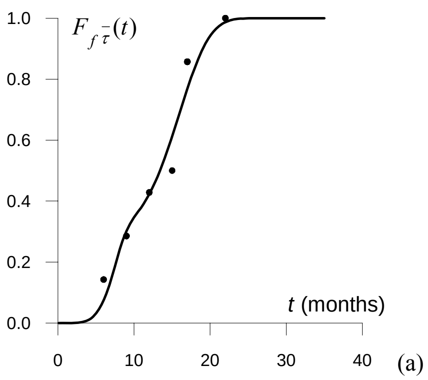
3.1 Damage Index

Denoting *iv* the generic vulnerability index, the deterioration over time *t* of a structure can be measured by using a time-variant damage index $v(t)$ as follows:

$$iv(t) = iv_0[1 + v(t)] \tag{1}$$

where iv_0 is the value assumed by the parameter *iv* in the initial state. A general form of the damage index can follow the form proposed by Biondini et al. in Ref. [15]:

$$v(t) = \begin{cases} \omega^{1-\rho}\tau^{\rho} & , \tau \le \omega \\ 1-(1-\omega)^{1-\rho}(1-\tau)^{\rho} & , \omega < \tau < 1 \\ 1 & , \tau \ge 1 \end{cases} \tag{2}$$



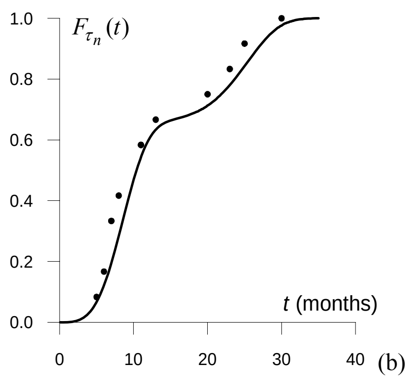


Fig. 5 (a) First waiting time ${}_f\bar{\tau}$ comparison between the cumulative distribution of test data (•) and curve-fit by two Weibull distribution (—); (b) Waiting time τ_n: comparison between the cumulative distribution of test data (•) and curve-fit by two Weibull distribution (—).

where $\tau = t/T_f$, T_f is the time instant of reaching the failure threshold $v = 1$, ω and ρ are damage parameters defining the shape of the damage curve.

The damage parameters ρ and ω must be chosen according to the actual evolution of the damage process. Damage rates may be associated to the aggressiveness of the environment and the level of other acting actions with respect to referring vulnerability index $\overline{iv}$, or $\xi = iv/\overline{iv}$. In this study, the following linear relationship is assumed [15]:

$$\rho = \rho_e + (\rho_l - \rho_e)\xi \quad (3)$$

$$\omega = \omega_e + (\omega_l - \omega_e)\xi \quad (4)$$

where the subscript "*e*" refers to damage associated with environmental aggression, and the subscript "*l*" refers to damage associated with loading effects and other actions. In this way, the proposed damage law is able to represent damage mechanisms induced by environmental deterioration, like carbonation of concrete and corrosion of reinforcement, capillary rise salt crystallization and delamination of masonry, or material fatigue. Generally, these mechanisms are present and interacting, and a proper calibration of the damage parameters is required based on experimental observations and/or laboratory accelerated test data.

3.2 Monte Carlo Simulation

The deterioration due to environmental aggressions and aging leads the structural system to move through different service states and the deterioration process can be model as a Mrp [1].

Supposing to identify states characterized by different level of vulnerability the evolution of the index *iv* over time becomes an important issue. But, the experimental databases are to small to study this evolution of *iv* under a probabilistic point of view, therefore a Monte Carlo simulation of the life-cycle structural performance based on the damage modeling previously introduced has been developed. In this simulation process the damage parameters ρ_a, ρ_b, ω_a, ω_b, and T_f, are modeled as random variables with prescribed probability distributions (Table 1).

The choice of the distributions was leaded by experimental evidence and the mean μ and standard deviation σ were estimated on the basis of laboratory and in situ accelerated damage tests developed in the laboratories of Department of Structural Engineering of Politecnico di Milano [13]. The choice made can not be considered as the "unique possible choice"; on the contrary, we are conscious that this delicate matter requires more attention and it will be the first aim of the authors in the development of the research.

Starting from a initial iv_0 the Monte Carlo simulation describes the evolution of *iv* as a time dependent variable *iv*(*t*) following the procedure previously introduced (Eqs. 1-4). The simulation was based on 20 random values for the parameter ρ_e, ρ_l, ω_e, ω_l, and T_f, each other combined, to build a population of 2000 samples. Fig. 6 shows the results obtained for two different iv_0: iv_0 = 16 (moderate damaged structure); iv_0 = 40 (damaged structure).

Fig. 6a is evident the similar evolution of deterioration due to environmental aggressions for the two different iv_0, in fact it affects only the materials not the whole structure; it has a major importance on the vulnerability of less damaged structure than on damaged one: when structures are affected by a high level of damage other factors play a greater role on the failure than the material deterioration.

The *iv* values obtained in a given instant t=t* represent the whole panorama of *iv* values that a building having a certain iv_0 at the instant t=0 can assume at the instant t = t*, as it was approached by Colonna et al. in Ref. [2] only on the basis of data recorded on real samples. The modeling of this panorama with an appropriate distribution is a suitable

Table 1 Probability distribution of random variables.

Random variables	Distribution	μ	σ
ρ_e	Normal	1.20	0.07
ρ_l	Normal	1.80	0.07
σ_e,	Normal	0.40	0.07
σ_l	Normal	0.37	0.07
T_f,(years)	Weibull	45.00	4.25

probabilistic interpretation of the behavior at the time $t = t^*$ of each building having iv_0 at the instant $t = 0$. Fig. 6b shows the comparison between the system state evolution over time for $iv_0 = 16$ and $iv_0 = 40$.

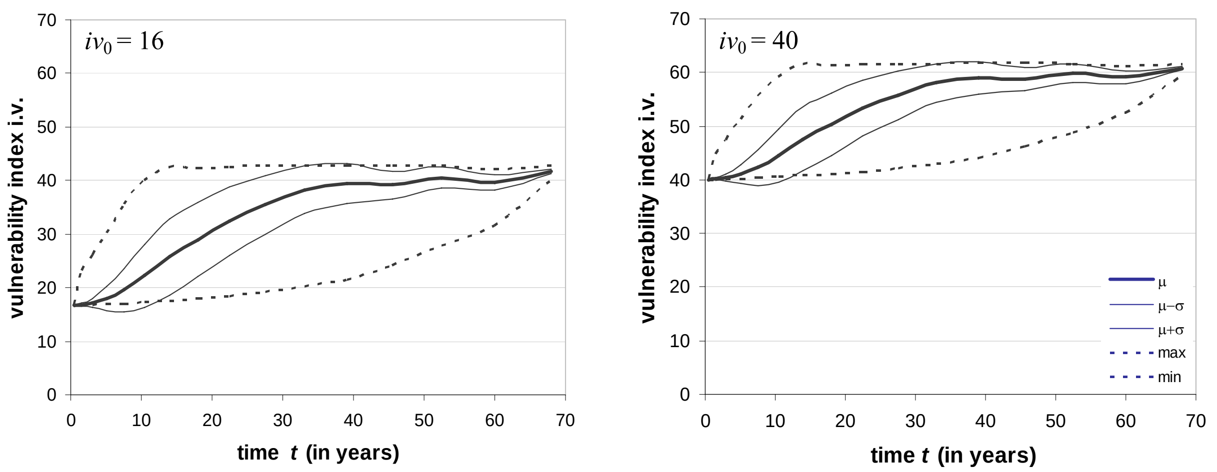
As a conclusion, the information contained in the $iv(t^*)$ behavior over time allow to connect the definition of iv (as in Fig. 3) with the natural aging process and consequently allow:

– to individuate within behavioral laws as those shown in Fig. 3, significant successive states i_1, i_2, ... that will be occupied by the system at present in state i, during the natural aging process; the undamaged state i_0 can be occupied by the system only as initial state, that is at t=0;

– to evaluate the connected lifetimes τ_1^i, τ_2^i, ... of the system in i_1, i_2, ... in the natural aging process; they depends on τ_n, the interoccurrence time between two failures that defines the delamination process as Mrp (section 2.2).

4. Building Damage Process in s-Mp Hypothesis

On the basis of the above mentioned results a s-Mp is introduced to represent the building damage process as the evolution process of the sample-building of the seismic zone that, over time, changes its state–iv because of: earthquakes, natural ageing phenomena and decisional rehabilitation strategies of maintenance,



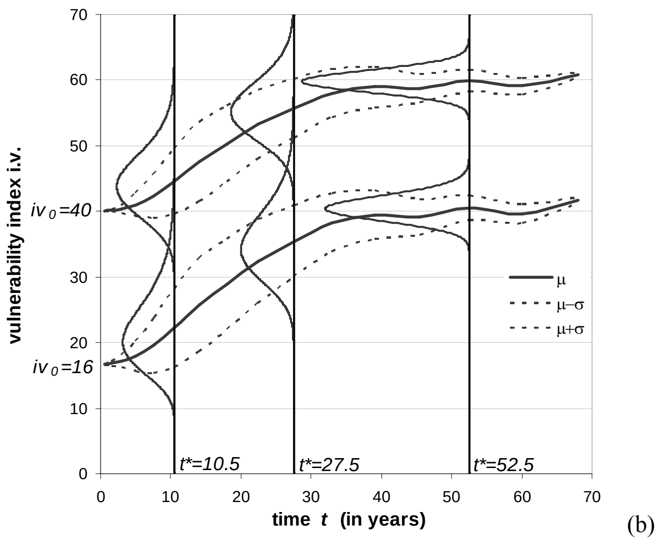


Fig. 6 (a) *iv* evolution over time for 2 different iv_0: mean μ (thick line), standard deviation σ from the mean μ (thin lines), minimum and maximum values (dotted lines). (b) Modeling of the deterioration process: comparison between iv_0=16 and iv_0=40.

damage repairing or anti-seismic improvement.

A s-Mp is a process whose successive state occupancies are governed by the transition probabilities p_{ij} of a Markov process, but whose stay in any state is described by a positive random variable τ_{ij} that depends on the state presently occupied and on the state to which the next transition will be made.

Therefore a s-Mp is one step memory process describing the evolution of a system that changes its state at each transition; it is defined when the following quantities are known [11]:

(1) Initial conditions: the initial state ${}_f i$, i.e., the state occupied by the system at the origin time t=0, and the elapsed time ${}_e\tau^i$, the length of time spent in the initial state at time t=0.

(2) Probability density function $h_{ij}(t)$ of the holding time τ_{ij}, i.e., the time spent in state i if the next state is j.

(3) Transition probability matrix p_{ij}, defined as: p_{ij}= *Pr{next state j, presentstate i}*.

In the considered case, the state i of the system is defined within the behavioural laws in Fig. 3; p_{ij} and h_{ij} with $i < j$ describe damage transitions of the system; p_{ij} and h_{ij} with $i > j$ are control variables of the system and thus depend on the chosen rehabilitation strategy.

As a first step of analysis, only damage repairing interventions, carried out immediately after every earthquake, are considered.

Therefore the following states of the system have to be distinguished:

(1) states i_1 , i_2 ,... i_n , defined as i-deteriorated states successively occupied by the system in the natural ageing process. As above shown these states can be defined within the behavioural laws in Fig. 3;

(2) states i^*, i^{**}, ... c, defined as i-damaged states, occupied by the system after an earthquake (where the number of $*$ denotes the subjected damage level, c is the maximum damage considered). The states i^*, i^{**}, ..., c, can not be defined within the behavioural laws in Fig. 3; they are defined by damage repairing costs.

(3) states i_r , i_{1r} , i_{2r} ,... defined as i-repaired states, occupied by the system after the repairing interventions carried out immediately after every earthquake; they are defined by the behavioural laws that describe state i_1 , i_2 , ... i_n , respectively.

It means that an earthquake transition is defined as an instantaneous transition $i\rightarrow$ *i-damaged* $\rightarrow i_r$,where i and i_r are defined by the same behavioural class i ; they differs within the holding times sequence that defines the building time history.

As a conclusion the introduced s-Mp is defined s follows; the system transitions are shown in Fig. 7 as it regards the holding times r_{ij}; as it regards the transition probabilities p_{ij} , they are:

$$
\begin{aligned}
&p_{i_n i_n} = F_{f\tau_s}(\tau_1^i + \tau_2^i + ... + \tau_{n+1}^i)\cdot F_Y(Y_I^{i_n}),\\
&p_{i_{nr} i_{nr}^*} = F_{f\tau_s}(\tau_1^i + \tau_2^i + ... + \tau_{n+1}^i)\cdot [F_Y(Y_*^{i_n}) - F_Y(Y_I^{i_n})],\\
&.\\
&.\\
&.\\
&p_{i_n} = F_{f\tau_s}(\tau_1^i + \tau_2^i + ... + \tau_{n+1}^i)\cdot [1 - F_Y(Y_C^{i_n})],\\
&p_{i_n i_{n+1}} = 1 - F_{f\tau_s}(\tau_1^i + \tau_2^i + ... + \tau_{n+1}^i)
\end{aligned}
\tag{5}
$$

where: n=0,1,2,....m and $i_0 \equiv i_f$,

$$
f_{f\tau_s} = \frac{f_{\tau_s}(t+t_0)}{1 - F_{\tau_s}(t_0)}
$$

$$
p_{i_n^* i_{nr}} = p_{i_n^{**} i_{nr}} = ... = p_{C\, i_{nr}} = p_{i_n i_{nr}} = 1, \tag{6}
$$

$$
\begin{aligned}
&p_{i_{nr} i_{nr}} = F_{\tau_s}(\tau_{n+1})\cdot F_Y(Y_I^{i_n}),\\
&p_{i_{nr} i_{nr}^*} = F_{\tau_s}(\tau_{n+1})\cdot [F_Y(Y_*^{i_n}) - F_Y(Y_I^{i_n})]\\
&.\\
&.\\
&.\\
&p_{i_{nr}\, C} = F_{\tau_s}(\tau_{n+1})\cdot [1 - F_Y(Y_C^{i_n})],\\
&p_{i_{nr} i_{n+1}} = 1 - F_{\tau_s}(\tau_{n+1})
\end{aligned}
\quad , \tag{7}
$$

$$
\begin{aligned}
&p_{i_{rn} i_{rn}} = p_{i_n i_n};\\
&p_{i_{rn}\, i_{rn}^*} = p_{i_n i_n^*};\\
&.\\
&.\\
&.\\
&p_{i_{rn} i_{r(n+1)}} = p_{i_n i_{n+1}}
\end{aligned}
\quad , \tag{8}
$$

where i_{rn} implies the following successive n+1 transitions of the system: $i\rightarrow i_r$ due to an earthquake;

$i_r \rightarrow i_{r1} \rightarrow \ldots \rightarrow i_{rn}$ due to the n successive natural ageing transitions.

5. Expected Rewards

The probabilistic structure of the s-M models allows the possibility of attaching rewards to the process.

Referring to the damage-rehabilitation process we are considering, the following reward model is assumed: when the transition from state i to state j is actually made at some time τ, the process earns a bonus $b_{ij}(\tau)$. The bonus is a lump sum payment at the time of a transition; it depends on the transition made and on the holding time in state i preceding the transition; the only requirement for bonuses is that they be real members, thus they may be costs.

In particular the bonus b_{i^*ir} , $b_{i^{**}ir}$ ... , b_{cir} are introduced as damage repairing costs after every earthquake. The expected present value of all future costs generated by the process, being ${}_f i$ the initial state, is given by the following functional:

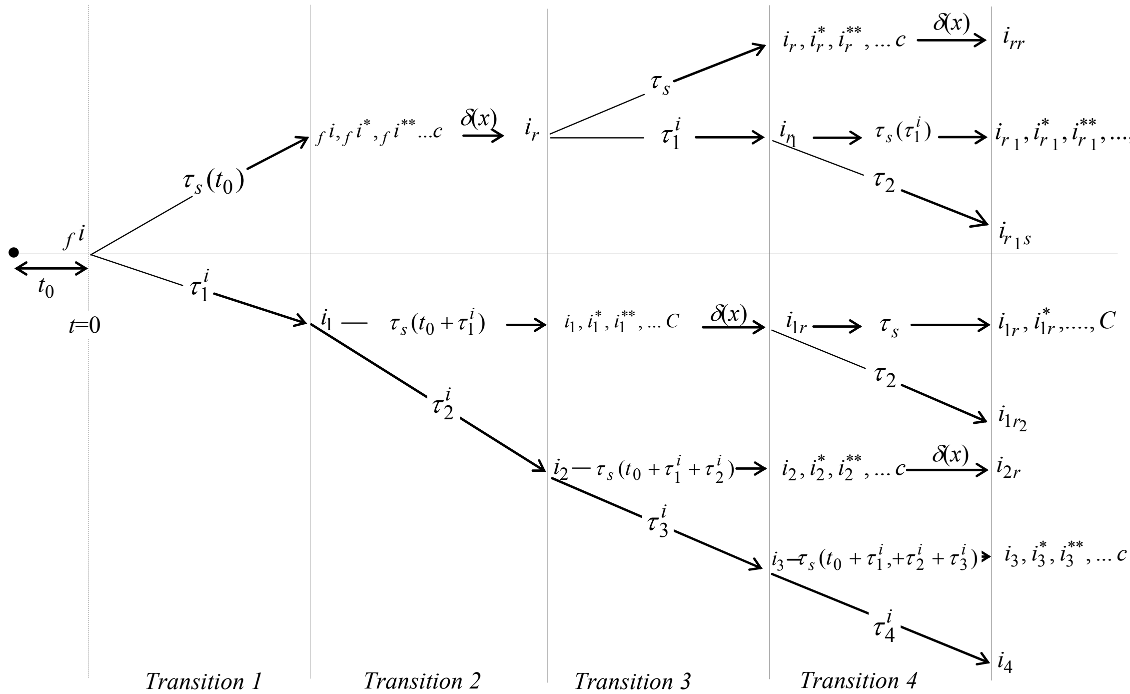


Fig. 7 The successive holding times τ_{ij} of the process. $\delta(x)$ denotes the impulsive function.

$$E_{fi}(t_0,\infty,\gamma)=\int_0^\infty dt\, e^{-\gamma t} f_{f\tau_s}(t,t_0)\cdot[p_{fi\,fi^*} b_{i^* i_r}(t+t_0)+p_{fi\,fi^{**}} b_{i^{**} i_r}(t+t_0)+\ldots+p_{fiC}\, b_{C i_r}(t+t_0)]+ \\ +\int_0^\infty dt\, e^{-\gamma t}[f_{f\tau_s}(t,t_0)\cdot p_{fii_r} E_{i_r}(\infty-t,\gamma)+f_{\tau_1}(t)\cdot E_{i_1}(t_0,\infty-t,\gamma)] \tag{9}$$

where γ is the discount rate and p_{fii_r} is given by:

$$p_{fii_r} = p_{fi\,fi} + p_{fi\,fi^*} + p_{fi\,fi^{**}} + p_{fiC}$$

The obtained results can be considered significant as they allow a homogeneous reading of damage processes of masonry with their multiple causes. Moreover the results allow to simplify the evolution of the synergies between the different types of damage processes and to simplify, at the same time, the evolution of connected risk.

6. Conclusions

The modelling of the damage evolution of historic masonry constructions due to catastrophic events (e.g., earthquake) requires the modelling, in probabilistic terms, of the process of the events causing it. On this matter it is important to define the present health state of each construction and its propensity to the damage for each possible future event; usually this step is not simple because of, for each building, the propensity of the damage is strictly connected with the direct causes of it.

On the contrary, in the modelling of aging or wearing phenomena, so as the modelling of the progressive damage affecting constructions immerged into an aggressive environment, the definition of the building's health state and its evolution over time is not a difficult matter, instead very complicated is the modelling, in probabilistic terms, of the process of the environmental attacks inducing damage.

However, in both cases the damage process seems to be governed by an accumulation and release of energy (fault mechanism for earthquake; crystallization/delamination mechanism for environmental aggressions), therefore, to model both these aspect of the problem seems to be opportune the use of probabilistic models similar in their mathematical frame. In this paper a Markovian renewal process (Mrp) is proposed to describe the damage process both in the case of catastrophic events, and in the case of natural aging.

The preservation of the historical heritage buildings is an important problem concerning the evaluation of "the total cost of intervention", which includes all the future damage costs. As underline in the paper, the total cost of intervention represents a suitable measure of the expected deterioration risk and its evolution obviously depends on the damage process which buildings are subjected to.

In the hypothesis of a Markovian renewal process (Mrp) describing the damage process, the total cost of all the future damage has been evaluated taking into account both the damage aspects: damages due to catastrophic aspects and damages due to aggressive environment. A semi-Markov process (s-Mp) has been defined to model the damage rehabilitation history of buildings in presence of seismic events, natural ageing and rehabilitation strategies.

The expected rewards connected to the process have been defined; they represent a significant measure of the risk. The obtained results by the expected rewards analysis, presented in section 5, can be considered significant as they allow a homogeneous reading of damage processes of masonry with their multiple causes. Moreover the results allow to simplify the evolution of the synergies between the different types of damage processes and to simplify, at the same time, the evolution of connected risk.

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