On-line monitoring and resilient design for a longer construction life

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Abstract

The lifecycle performance of constructions exposed to seismic risk needs a more sustainable design philosophy. The technical norms stand on the concept of "performance based design" where "performance" means mainly "structural safety".
The more recent earthquakes show that the structures can survive but allow heavy damages on non-structural components. The global cost, including damaged components removal and replace or repair, failure of technical installations and production facilities, social and economic life interruption, hosting elsewhere people and jobs, can be unbearably high and deny the expectation of effective prevention.
The concept of "resilience based design" is a more efficient choice. The resilience is the attitude to limit and confine damages and to recover functionality demanding short time and low global cost. The adoption of some very simple design criteria and a good maintenance supported by robust on-line monitoring actions can strongly help;

Keywords: Resilient design, Sustainability, On-line monitoring, Symptom space, Principal component analysis

1. Resilient design criteria against earthquakes

1.1 An illuminating case: the Lu Shan Hospital (Zhou, F. L., et al. (2013))

The Lu Shan hospital is an illuminating case for two reasons:

- It stresses-out, once more and dramatically, how much it can be misleading the use of the probabilistic approach and its application in the technical norms of several Countries to predict and define the design earthquake.
- It helps us to understand how much it is important to reduce the displacement of the structure beyond the elastic limit to make "resilient" the seismic behaviour of a construction or infrastructure system.

The *Lushan* event caused 196 deaths (besides 21 missing people) and the wounding of 250,000 people. About 40,000 buildings (i.e. about 75% of those in the area affected by the earthquake) collapsed or were damaged. Many strategic and public buildings (including schools and hospitals) even constructed or reconstructed after the Wenchuan event, were severely damaged.

The Lu Shan county hospital (7 floors above ground and one basement), consisted of two buildings with conventional foundations and one with base seismic isolation supplied by 83 LRBs (Lead-Rubber Bearings). The effectiveness of the seismic isolation can be quantified in a reduction factor of the roof maximum acceleration equal to 6.

The following table 1 contains a basic seismological information:

Table 1: Wenchuan and Lu Shan earthquakes

Name and location	date	Magnitude	Casualties
Wenchuan (Sichuan, western China)	2008, May 12	8,1	87587
Lu Shan (150 km from Wenchuan)	2013, April 20	7,0	199 (250.000 injured)

Figure 1. The Lu Shan Hospital: The body 1 is base isolated; the two bodies 2 have traditional foundations.

A reliable prediction of the seismic action to be taken into account in the structural design is a first, fundamental step towards a resilient, sustainable construction. Technical norms base that prediction on probabilistic criteria, generally built on the Gutenberg-Richter law or on the Poisson distribution. The Italian NTC-2008, e.g. uses the exponential rule that is a special application of the Poisson process.
Following such rule the following Table 2 shows the relationship of reference time interval n, probability of exceeding a given seismic intensity threshold I_0, at list once in n years, and the Return Time RT, i.e the average expected repetition time interval. If we need to design, e.g., a critical industrial facility and use a design earthquake with 2% probability of overrun in hundred years, then the design earthquake will have average expected repetition time interval of about 5000 years. The I_0 intensity threshold is relatively very high. Let us suppose that we know by sure (for absurd hypothesis) that an earthquake with I_0 intensity happened 5000 years ago, without any further similar or more severe event in the past 5000 years. Following the exponential process rule, which probability can we expect of a replica in the next year? Answer: more than 60%.

Table 2: Return time (in years) given the probability of excedance P of the threshold I_0 in n years

	n = 10 anni	n = 50 anni	n = 100 anni	n = 200 anni
RT ($P[I \geq I_0] = 10\%$)	95	475	950	1900
TR ($P[I \geq I_0] = 2\%$)	495	2475	4950	10000

In fact:

- we know with sufficient accuracy the seismic history in many countries only for the past 150-200 years;
- earthquakes are geophysical events not enough well known yet. They cannot be described by a pure stochastic distribution;
- the statistics of small-medium frequent earthquakes can help in understanding better the mechanical behaviour of the earth crustal layer but not necessarily are useful to assess the statistics of strong motions.
- The strong motion expectation cannot be based on empty and arbitrary distributions, containing no data, without memory, supposed invariant in time. Treating as very improbable a strong motion because its Return Time is long is dangerous. The unknown geophysical history and mechanism can increase the hazard in unpredictable way.

The concept of Return Time itself, then, is a purely statistic concept, not meaningful for prediction purpose. Going back to the Lu Shan case, two very strong earthquakes happened in five years in locations distant 150 km. Many similar cases can be found in history; in California (San Fernando, Loma Prieta), in Turkey (Marmara sea, 1999, two strong quakes in six months), in Chile...

The largest part of the strongest motions worldwide in recent years were underestimated by the design prescriptions in the technical norms. To build “resilient” constructions in seismic prone areas the first need is to avoid such underestimation by a correct hazard evaluation. An alternative proposal to reach this goal is the so called “Neo Deterministic Seismic Hazard Assessment” (NDSHA, e.g.: Peresan,A. et al (2008)), in which a “Maximum Credible Earthquake” is proposed for each site, on the base of multi-criteria geophysical analyses and earthquake scenarios. Probabilistic and neo-deterministic approaches are complementary and should be considered together, without any ideological rejection and a lot of work and refinement to do.

1.2 The construction as a global body; facing the global cost.

The second lesson that the Lu Shan hospital case teaches us is that the structural and human life safety is not enough. The ground-restrained bodies of the hospital did not collapse, but their functionality were inhibited. Due to the 2013 earthquake, 250.000 people were injured. It is not important that they were not injured inside the hospital: it is important that the hospital could provide medical care just because one among the three bodies of the it were base-isolated and could remain active and functional during and immediately after the earthquake.

“Resilience” means “ability to confine and mitigate the damage and to guarantee a fast and low-cost functionality recover”. Resilience is a key-word towards sustainability and the concept of “global cost optimization” oriented design.
The global cost includes: construction, maintenance, damage repair and retrofit, temporary dwelling elsewhere, temporary function interruption. The resilience is a recent engineering discipline that is building strategies, algorithms, simulations, generally at the level of urban or infrastructure systems. It is a discipline attaining the complexity domain, as it often happens in system oriented engineering. Nevertheless it is possible to offer simple and effective contribution at the level of single constructions, helping in practical way to realize or improve the system resilience. Structural design and construction should follow two basic principles:

1. the structural components bearing the vertical loads shall not be responsible primarily of the bearing capacity and safety against earthquakes,
2. the structural components bearing the vertical loads shall not be pushed to significant non-linear response; they should remain inside the domain of nearly linear behaviour.

In simple concepts the responsibility of taking charge of the horizontal seismic actions should be assigned as much as possible to components not bearing vertical loads; a significant non-linear behaviour of the structural components supporting vertical loads should be avoided (never accept a ductility demand exceeding 1.5). The goal is to reduce as much as possible the damage suffered by non-structural components and, consequently, to mitigate the global cost and make the construction resilient. Thus, what about the emphasis on the ductile response and capacity design, common to most of the existing technical norms? It is welcome, of course, but it should be finalized to improve the “available ductility”, a useful safety reserve, not to increase the “requested ductility”, i.e. the ductility strictly necessary to survive during a strong earthquake, paying it with a large amount of plastic deformation and displacement and distributed damage.

Following the two above mentioned principles, then, we can try to understand how to apply them in practice. The ground motion induced by the earthquake contains a large amount of energy. The mitigation of the destructive earthquake impact depends fundamentally on the capacity of sustaining, reducing or dissipating the energy that the ground transfers to the structure. The seismic isolation, like in the case of the Lu Shan hospital, strongly limits the energy transfer from the ground. The largest part of the energy remains confined in the soil and does not migrate into the building structure. The base isolation acts as a low-pass filter; only low frequency harmonic spectral components pass from the ground to the construction body, moving with large relative displacements but small value of the acceleration.

Rubber bearing device
(FIP Industrial)

Curved surface sliding device
(Courtesy Maurer & Soehne)

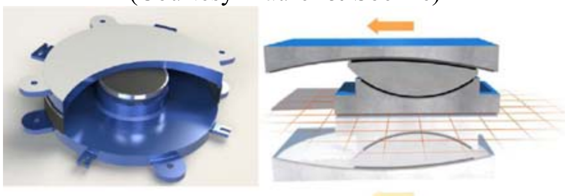
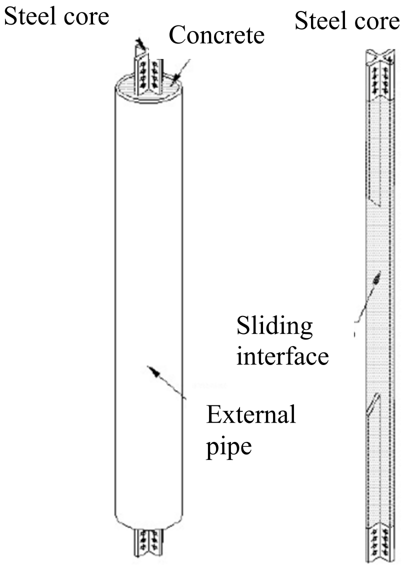


Figure 2: most commonly used base isolation device types

By adding shear walls or braced frames to the structure we can obtain a significant strength gain, making the structural body able to sustain the energy transfer with the help of a moderate but necessary dissipation capacity and consequent limited damageability. Artificial dissipative braces can be very useful. Their hysteretic behaviour is well predictable; they should be significantly more stiff than the structure in which they operate, in such way that their hysteretic energy dissipation can fully work while the structural components bearing vertical loads are still inside or only slightly beyond the elastic limit. In figure 3 an application of BRBF (Buckling Restrained Brace Frames) hysteretic dissipative devices is shown.

Buckling restrained brace



BRB Frame

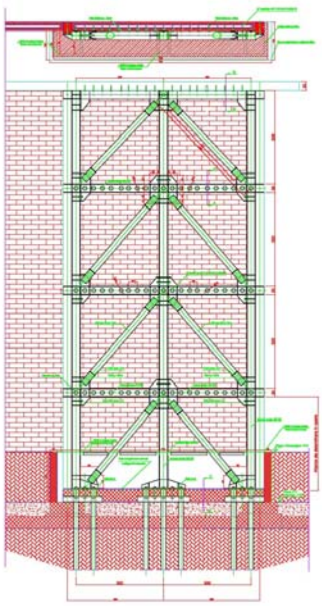


Figure 3: an effective dissipative device

The realization of resilient structure is a step ahead towards the sustainability and prevention. To reason in terms of global cost is more and more important, but every step towards the prevention of seismic damage and collapse is ruled by the constraint imposed by the limited available financial resources.
Priority criteria are necessary; they lay on careful risk analysis. Hazard and vulnerability, together with the exposition, contribute to risk. The problem of the hazard prediction has been touched previously; the vulnerability is the intrinsic damageability of a construction. The shape, the geometrical and mechanical properties determine the vulnerability, but a strong influence comes from the time

dependent degradation and aging and the history of past damages, manipulations and lack of correct maintenance. Monitoring can play a very important role.

2. Risk, reliability, symptoms and damage.

Risk and reliability are probabilistic concepts. Often, in literature, the stochastic variable is time, and the probability is the probability of time delay to the occurrence of a pre-defined damage limit state. The probabilistic distribution becomes a stochastic process in which time dependent material degradation, fatigue problems and the prediction of residual life can be easy to model and easy to combine with the risk analysis related with environmental offences, like earthquakes, floods, strong winds, landslides. The reliability of a structure, $R(t)$, is defined, then, as the probability that the time to reach a reference limit state, t_b, is greater than a given time t (Lawless, 1982):

$$R(t) = P(t \le t_b) \quad (1)$$

The hazard function, $h(t)$, specifies the instantaneous rate of reliability deterioration during the infinitesimal time interval, Δt, assuming that integrity is guaranteed up to time t:

$$h(t) = \lim_{\Delta t \to 0} \frac{P\left(t_b < t + \Delta t \;\middle|\; t_b \ge t\right)}{\Delta t} \quad (2)$$

In case of smooth time-dependent degradation phenomena, $h(t)$ can be correlated to the reliability function, $R(t)$, by the following relationship:

$$R(t) = \exp\left(-\int_0^t h(x)\, dx \right) \quad (3)$$

On the other side, the hazard function allows to include into the prediction algorithm, as spikes and jumps, also the sudden and singular events like earthquakes, floods and other environmental threats. Nevertheless, following such path, it results not trivial to include into the risk analysis the advantages offered by the application of on-line condition monitoring.

To mark the role of the on-line monitoring it is convenient to jump from the time domain into the symptom space. The symptom hazard function, $h(S)$, is the reliability loss rate versus the symptom increase rate; then reliability can be rewritten as a function of the symptom variable, S, as it is the probability that a system, which is still able to meet the requirements for which it has been designed, displays a value of S smaller than the value S_b corresponding to the reference limit state (Cempel et al., 2000):

$$R(S) = P(S \le S_b \;|\; S = \text{suitable value}) = \int_S^\infty f_S \, dS \quad (4)$$

and

$$R(S) = \exp\left(-\int_0^S h(x)\,dx \right) \quad (5)$$

This formulation includes continuous time (slow degradation) or/and discrete time processes (earthquakes, storms, etc.), given that time and symptom evolution can be correlated by suitable lows.
So, as focused above, the Condition Monitoring is essentially a search for structural or material disease symptoms. Symptoms can be regarded as evolutionary and sudden changes in observable qualitative properties and/or measurable responses. Symptoms search can require a knowledge based direct search or model based predictive assessment. In both cases a stochastic procedure is needed. In some applications direct search and model based simulations can provide an integrated procedure.
In the works by Cempel (see, e.g., Cempel, 2003) the symptom based on-line SHM is applied to mechanical systems, mainly machines. Mechanical systems can be often grouped into types and classes with common properties. Large experimental data-bases are in many cases available and accessible; this makes it possible to use symptoms to detect damage on knowledge base. That approach, known also as "Holistic Dynamics", does not need a reference F.E. model.

2.1. A robust Condition Monitoring approach

The approach proposed by Cempel, well fitting the definition of "robustness" given above, is here discussed in some detail.
Mechanical structures in operation and machines vibrate. Measuring vibration signals and processing provide symptoms of condition. Symptoms are evolving (usually growing) during the system life, giving good mapping of operational condition of a system. Referring to existing historical knowledge bases it is then possible to develop 'go/repair' decision rules which ultimately lower the risk of operation. Such is the idea behind condition monitoring of a system: from signals to symptoms and to system condition.
In traditional approaches, this is usually done on the basis of one symptom–one condition measure. The measuring technology of today, however, enables to measure many life-dependent operational and residual processes as symptoms, therefore allowing the creation of symptom observation matrices.
Cempel exploits such multidimensionality of the symptom space in order to elaborate some independent measures and indices as inference tools with good confidence level. The multidimensional approach is made possible by the use of the transformed symptom observation matrix (SOM) and by successive application of singular value decomposition (SVD). On this basis, one can obtain full extraction of fault-related information from symptom observation matrix by traditional monitoring technology, and also create several independent fault measures and indices. In other words, SVD allows to pass from the multidimensional-non-orthogonal symptom space to the orthogonal generalized fault space, of much reduced dimension. This seems to be important, as it can increase reliability of condition monitoring of critical systems in operation and can maximize the amount of condition-related information in the primary symptom observation matrix, pushing towards a redesign of traditional CM systems.

Symptoms may be any measurable or observable quantity which is sensitive to system modifications. Additionally, symptoms should be sensitive to damage evolution but insensitive to distorsions. Direct reference (Cempel, 2003) is made to vibration measurements as helpful symptoms, particularly as the average (or root mean square) values of the time-history records over some time-span, but various kinds of either global or local symptoms can be generally chosen, including constants, functionals, vectors, functions, field descriptions, either taken as the response to operating/service forces or as the response to purposely applied test forces. Supposing now that r symptoms S_m, m = 1, 2, …, r, are measured at p instants θ_n, n = 1, 2, …, p, over the system life, the observation matrix may be defined as:

$$O_{pr} = [S_{nm}] = [S_m(\theta_n)], \quad n = 1, 2, \ldots, p, \quad m = 1, 2, \ldots, r \tag{6}$$

with m as the number of columns (symptoms) and n as the number of rows (lifetime readings). When symptoms are well chosen and the system operation is stable, the observation matrix is a valuable resource concerning the system condition and evolution of the system properties.

Since, in general, the observed symptoms have different physical origin and therefore different physical units, range and initial values, it has been stressed out (Natke & Cempel, 2001) that the subsequent feature extraction is improved if O_{pr} is preliminarily normalized, i.e. every symptoms is first column-like divided by its initial value and then centred on it. Furthermore, since many critical structural systems operate in a non-stationary load regime, and many observed symptoms depend in some way on load and/or environmental conditions, the CM of such systems should have some possibility of rescaling of the observed symptoms to a standard generalized load condition (Cempel & Tabszewski, 2007).

In fact we will show later that normalization and re-centering actions can be performed repeatedly inside a single analysis process if it is helping to extract a more significant information.

The observation matrix can be a huge matrix. Some symptoms can be correlated with others and unusefully redundant. This is why, the normalization above being accomplished, singular value decomposition (SVD) can be profitably applied to SOM in order to extract different generalized fault modes evolving in the system:

$$O_{pr} = U_{pp}\Sigma_{pr}V_{rr}^T = \sum_{t=1}^{z}\sigma_t\left(u_t v_t^T\right) = \sum_{t=1}^{z}\left(O_{pr}\right)_t, \; z = \min(p, r) \tag{7}$$

where t = 1, 2, …, z, σ_t are the singular values, u_t and v_t the (orthogonal) singular vectors, as columns of the respective matrices U_{pp} and V_{rr}.

Given that, in general, p is greater than r, naming l the effective rank of O_{pr} a more comfortable formulation of (7) is convenient:

$$O_{pr} = U_{pr}\Sigma_{rr}V_{rr}^T = \sum_{t=1}^{l}\sigma_t\left(u_t v_t^T\right) = \sum_{t=1}^{l}\left(O_{pr}\right)_t, \; l \leq r \tag{7bis}$$

As a result of SVD, the symptom observation matrix O_{pr} is represented as the summation of l independent matrices $(O_{pr})_t$, each describing a specific mode t of system operation modification (evolution), or generalized fault mode. Tracing the evolution, through the lifetime θ, of the fault modal parameters, $\sigma_t(\theta)$, $u_t(\theta)$, $v_t(\theta)$ and $(O_{pr})_t(\theta)$, gives an understanding of the system conditions. Especially useful is the time evolution of the so-called generalized fault symptom: $SD_t(\theta) = O_{pr}(\theta)\cdot v_t(\theta) = \sigma_t(\theta).u_t(\theta)$, which represents a weighted summation of the symptom values for each lifetime θ and can be shown to give information on both the shape of a generalized fault and its energy.
It can also be easily shown that singular values and singular vectors in the SVD can be equivalently obtained through solving the eigenvalue problem for the matrices $W_1 = O_{rp}{}^T O_{pr}$ and $W_2 = O_{pr}O_{rp}{}^T$. In particular, the matrix W_2 is similar to the correlation/covariance matrix in stochastics: through its values, it characterizes the orthogonality between the lifetime-dependent symptom vectors. Also, it gives information on the quality of the choice of the vectors with respect to the lifetime modifications: large values of the out-of-the-main-diagonal elements indicate linear dependency of the symptoms, which means redundant information with respect to θ.
Using both generalized fault indices $\sigma_t(\theta)$ and $SD_t(\theta)$, the first related to the intensity of wear advancement in a given fault mode and the second to its momentary shape, instead of the original symptom observations $O_{pr}(\theta)$, allows a more concise and powerful representation of system conditions. In this sense, SVD plays the same role of eigenvalue decomposition in system dynamics and of principal components analysis (PCA) in statistics.

2.2. The SVD intuitive meaning

To better understand the effectiveness and potential usefulness of the SVD as diagnostic tools, it is convenient, at this point, to enter more deeply into the algorithm itself and to reason on it from a more intuitive point of view. As stated above we suppose that the *Symptom Observation Matrix* $\boldsymbol{O}$ contains p observations of a selected number of symptoms (r symptoms). Let us assume that $p > r$ for sake of simplicity and recall the equation 7bis.

Each singular value can be regarded as a weighting coefficient defining the relevance of the related pair of singular vectors in recomposing the SOM $\boldsymbol{O}_{pr}$.

Suppose, now, that the If we chose an integer number $s < r$, the sum:

$$O_{approx-s} = U_{ps}\Sigma_{ss}V_{rs}^T = \sum_{t=1}^{s}\sigma_t\left(u_t v_t^T\right) \tag{8}$$

gives the s^{th} order approximation of $\boldsymbol{O}$, or, in other words, the reconstruction of $\boldsymbol{O}$ based on its SVD reduced rank s.
A well-known property of the SVD states that, given the choice of the reduced rank s, among all the sets of s orthogonal couples of vectors $\boldsymbol{u}_p$, $\boldsymbol{v}_r$, the left and right singular vectors extracted fron a s-ranked incomplete SVD, through the equation

(8), lead to the optimal reconstruction of ***O*** through weighted products of s pairs of orthogonal vectors, i.e to the minimum Frobenius norm of the matrix of residuals.
Such property lives also if $s = 1$. $\boldsymbol{O}_{approx-1}$ calculated by means of the first rank SVD is the optimal of ***O*** reconstruction obtainable by any pair of x_p and y_r vectors, i.e.: the residual matrix $\boldsymbol{O}_{res-1} = \boldsymbol{O} - \boldsymbol{O}_{approx-1}$ has the minimum norm among all the possible reconstructed approximations of ***O.***
Whilst $\boldsymbol{u}_1$, and then $\boldsymbol{O}_{approx-1}$, are sensitive to the slow condition changes and progressive degradation of material and structure, the SVD of the residual matrix is surely mor linked with sudden or local damages.

2.3 SVD measures of system conditions: The general rules for a good choice of symptoms

But what can be the equivalence between the wear characteristics and measures of the operating system and the SVD parameters?
From the physical viewpoint, different wear modes can occur like corrosion, fatigue, erosion, etc., but the influence of different types of wear modes working concurrently in a system in operation can be very similar, when observed in a symptom space, so we cannot differentiate them in this way. In other words, physically different types of wear can generate similar signals or symptoms, and there is no way of finding the expected difference in the resource of the symptom observation matrix. This means that the transformation from the space of physical wear to the symptom space is not unique and unequivocal. Hence, looking for fault description in the symptom observation matrix, only some generalized faults $F_t(\theta$ can be mathematically identified without getting to know their direct physical and/or operational origin. From that point of view, it is of paramount importance to proper choosing (physical origin, place of measurement, signal processing, etc.) each observed symptom $S_m(\theta)$ during the system operation. In general ***O*** can include heterogeneous vectors coming from various kinds of measures and observations. All the vectors shall be centered and scaled in way to have comparable norms.

If the symptoms are not correlated we can fail looking for diagnostic answers. Totally uncorrelated "symptoms", in fact, are not symptoms at all, they are measures or observations having no significant links with degradation processes or localized damages. The higher order singular values can generally remain large, comparable with respect to the first-one. The diagnostic response will be noisy and confusing.

On the other side, symptoms varying nearly in proportional way can cause a loss of information richness. They supply all the same answer as one symptom only. The ***O*** matrix has one dimension and higher order singular values will disappear or be negligible.

A good choice of symptoms can include, for instance, observations sensitive to a global evolution, like, for a beam, the mid-span displacement, and other sensitive to local phenomena but correlated with the former-one, like deformations or curvatures.

Since in a system in operation several generalized faults may be evolving concurrently, then it is important to know also the global advancement of all generalized faults in a system.
Hence, some global indices are needed. It can be shown that the best choice appears to adopt the sum of absolute values of singular values:

$$DS(\theta)=\sum_{t=1}^{z}\left|\sigma_t(\theta)\right| \tag{9}$$

as the measure of wear advancement, and the sum of absolute values of singular vectors:

$$P(\theta)=\sum_{t=1}^{z}\left|SD_t(\theta)\right| \tag{10}$$

as the measure of the generalized fault profile.
Summing up, it seems possible to pass from multidimensional symptom space with high redundancy to generalized orthogonal fault space with very few generalized faults $F_t(\theta)$. It is also useful to create some combined measure and indices on a system condition, in terms of some norms of the symptom observation matrix, its singular values, and SVD-related summary measures and indices.

3 Condition assessment on existing civil structures

Existing civil structures are generally non-standard, unique and non-constrained strictly into types and classes. At the beginning of the monitoring action useful data and knowledge bases are seldom available. Such situation configures the phase of initial assessment of the present state. From now on the analysis of damage evolution will move its steps.
Unfortunately the initial condition is not necessarily an undamaged condition, so its assessment shall include damage scenarios and their detection and identification.
The lack of real damage knowledge bases makes numerical simulation on F.E. models the only practical way. If only model based simulation is available, than the damage assessment using the Symptom Observation Matrix converges to the so called “multi-model approach” to model updating.
First, let us assume that the Symptom Observation Matrix allows to relate damage indexes to symptoms, originally intended as changes in modal and statistical parameters extracted from vibration signals, but extendable to more general symptom spaces.
Due to uncertainties and errors, we can assume that each damage state can generate infinite symptom sets, in which each symptom can change in agreement with a given probability distribution.
If we use models and simulation, probabilistic procedures (including Monte Carlo search) allow to generate many structural models by changing randomly material and mechanical properties; consequently, many sets of damage scenarios and symptom sets can arise.
The final goal is to extract damage states and their probability from the analysis of observed symptoms.
The size of the observation matrix, its multi-dimensional and multi-variate stochastic nature, non-linearities, intrinsically included in the real damage-symptom

causality and the randomness of measures and environmental conditions in which symptoms are extracted, make it hard to solve the inverse problem.

It is necessary to reduce the size of the problem and, at the same time, to prevent correlate symptoms treated as independent variables from generating noise and leading to incorrect solutions.

As for the "holistic dynamics" approach, the master path goes through the Principal Component Decomposition or Proper Orthogonal Decomposition, that are in fact different applications of the same technique, being both based on SVD.

By applying the single value decomposition to the observation matrix, conveniently normalized and transformed, the operational space is reduced and inversion made easier. In other words, full utilization of SVD enables to pass from multidimensional-non-orthogonal symptom space , to orthogonal generalized fault space, of much reduced dimension. This seems to be important, as it can increase the reliability of condition monitoring of existing structural systems in service. It enables also to maximize the amount of condition-related information in the primary symptom observation matrix, and redesign the traditional condition monitoring system.

This kind of approach contains an implicit idea of causality. If we want to reason in terms of "conditioned probability", instead of cause-effect, we can look at the condition monitoring using symptoms observation as a typical Bayesian problem. All model based characterization methods belonging to the class of "multi-model" approaches can be associated to the Bayesian stochastic theory. An example of a multi-model approach to characterize an ancient masonry structure will be shown later.

It is important to stress-out that this kind of philosophy is based on the choice of the best fitting solution among many candidates generated randomly in a direct way. In such a way the trap of the ill-conditioned nature of inverse approaches is avoided, although replaced by ambiguity (different models can fit equally well). The method is robust given that the initial choice of damage scenarios is correct and sufficiently exhaustive.

The multiple model approach to optimal model choice

The presence of damages and uncertainties inside an existing structural body makes that the mechanical properties of the structure are affected by a local variability that cannot be assessed a priori in deterministic way.

For these reasons, we wish to generate multiple models for achieving the right solution; but what do we mean by "multiple model"?

We can talk about multiple model approach in two different cases:

candidate models belong to different classes having different sets of parameters (heterogeneous model set);

all candidate models have the same structure with the same set of variables and differ only in the value of continuous variables (homogeneous model set).

In both cases different models can be representative of different "damage scenarios" so as they came out from a preliminary risk assessment.

However, the two situations are different in the face of data mining techniques. The first case is difficult to automate. Current data mining techniques are unable to accommodate data containing different sets of parameters. A semi-automatic procedure can be applied in the case of heterogeneous models where the user manually separate models into classes using their knowledge of important

parameters. On the contrary, data mining techniques may be very useful to discover different types of data patterns in the second case.
No matter which case is under consideration, the multiple-model approach consists of two distinct phases: the multi-model generation (generation phase) and the final selection of the best-fitting model/models (selection phase). (see for instance Smith et al., 2006).

4 Concluding remarks

Condition Monitoring is a tool to keep under control the health conditions of relevant structures and to help decision making related to maintenance priorities. CM requires distributed sensing systems (hardware) and reliable data treatment procedures (software). The present contribution does not enter deeply into the sensing technology. It has been stressed-out that distributed sensing means low-cost technologies. Until now the most of monitoring systems are based on point-wise sensing devices connected in networks. The modern trend, however, is towards physically distributed systems, where the construction and coating materials themselves have sensing capabilities. Vectorial properties of stress and strain fields will be replaced by scalar functions, which will require accurate interpretative models. Damage assessment procedures need to be robust to reduce the influence of local errors and uncertaities. The two methods above illustrated are focused on different goals, but they have several common aspects: both belong, in wide sense, to the domain of stochastic Bayesian methods; both rely on the quality of the damage scenarios that make the initial knowledge a base for simulations project. Both avoid inversion of large problems using data mining tools to reduce their size. Both allow a consistent physical and intuitive control on the outcoming results.

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4.3 The construction as a global body; facing the global cost.

Due to the workshop nature of ESReDA Seminars, strict rules about paper length are not imposed on authors. However we recommend that the paper be of maximum 12 pages in length. Please use these guidelines when writing your paper. By following them carefully you will contribute to reducing the time needed to issue the proceedings.

The body text of the paper should be Times New Roman 12pt, single line spacing, justified text. Please leave a 12 pt line space after each paragraph.
The text should be typed in one column. Sections should be numbered in sequential order. Lists can be formatted using either numbers or bullet points. Avoid making the lists too complicated a maximum of two levels is advised. They should be set out as shown in this paper.

Example of numbered list:

1. Start list with a capital letter. Times New Roman, 12pt, 1 cm tab, space before 12pt;
2. Times New Roman, 12pt, 1 cm tab, space after 12 pt.

Example of bullet point list:

- Times New Roman, 12pt, 1 cm tab, space before12pt;
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1.1.1 Third order heading tab 1 cm, Times, 12 pt, underlined, space before 12 pt.
When inserting tables into the text please make sure that you label and number (Roman numerals) each table clearly and remember to cite each table in the text. Leave a space of 24 pt before and after the table. Tables should be typed with a smaller 10 pt character. See for example Table I.

Table I: Insert here the table caption (Times 10pt, flushed left, space after 6 pt).

Times 10 pt bold	**xxx**	**xxx**	**xxx**
Times 10 pt	xxx	xxx	xxx
Double outside line 1/2pt	xxx	xxx	xxx
Line under heading 1pt	xxx	xxx	xxx
Thin lines 1/2pt	xxx	xxx	xxx

1.1.2 Third order heading tab 1 cm, Times, 12 pt, underlined, space before 12 pt.
When inserting figures (graphs, plots, diagrams, etc.) into the text please make sure that you label and number (Arabic numbering) each figure clearly and remember to cite each figure in the text. Figures should be placed as near as possible to their first reference. Please leave a space of 24 pt before the figure and after the figure caption. See for example Figure 1, [1]. Please limit the use of coloured figured and pictures to the really necessary cases, since reproduction in colour will be limited and not guaranteed for all figures.

Formulae should be clearly typed with an equation editor, centred and numbered in sequential order (if necessary) e.g.

$$R(t) = g(t) + \int_0^t R(t - u)\, dF(u) \qquad (1)$$

Refer to them in the text as e.g. eq. (1). Leave 12 pt space before and after each equation.

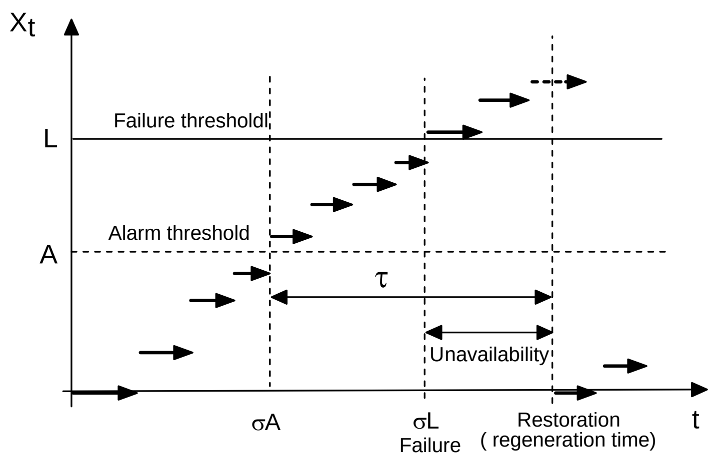

Figure 1. Evolution of the maintained system, adapted from [1]. (Figure caption, 10 pt, space before 6 pt, justified on the figure width).

Acknowledgements

Please insert acknowledgements, if any, before the references. G.G.M. Cojazzi and F. Lo Bue of European Commission, Joint Research Centre, Institute for Protection and Security of the Citizens, located in Ispra, Italy, have written these Instructions.

References (Times, bold, 14 pt)

Please use a coherent style for references; either by referring to them using numbers (Vancouver) or by author (Harvard).

Whether you chose to use the Vancouver or the Harvard style (demonstrated below) to format your references please make sure that all references listed are cited and that all cited references are listed in the reference list.

For citing Vancouver style references in the text you should use numbers in square brackets e.g.: [1], [2], [3], [1-7], [1, 7].

Vancouver style, references are listed in the reference section in order of citation e.g.:

[1] Dieulle, L., Bérenguer, C., Grall, A. and Roussignol, M. (2003) Asymptotic Failure Rate of a Continuously Monitored System, In: Sola, A., and Cojazzi, G.G.M. (eds.) *Maintenance Management & Optimisation*, *Proceedings of the 22nd ESReDA Seminar*, *Madrid, Spain, May 27-28 2002*. EUR 20760 EN, pp. 223-230.

[2] Procaccia, H., Arsenis, S.P. and Aufort P., Preface by Volta, G. (1998) *European industry reliability data bank EIReDA 1998*. Crete University Press.

[3] Toft-Christensen, P. (ed.) (1998) *Industrial Application of Structural Reliability*. ESReDA Safety Series No. 2, DNV, Høvik.

[4] Lannoy, A. and Procaccia, H. (1994) *Méthode avancées de traitement et d'analyse de banques de données du retour d'expérience*. Collection de la Direction des Etudes et Recherches d'Electricité de France, Editions Eyrolles N° 86, Paris.

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For citing Harvard style references in the text you should use the following formats:

Assmussen (1987), Cojazzi et al. (2001), Dieulle et al. (2003), Lannoy and Procaccia (1994), Procaccia et al. (1998), Singpurvalla (1997), Toft-Christensen (1998).

Harvard style, the references are listed in the reference section in alphabetical order:

Asmussen, S. (1987) *Applied probability and queues.* Wiley series in probability and mathematical statistics, John Wiley & Sons.

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