A pre-posterior analysis framework for quantifying the value of seismic monitoring and inspections of buildings

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Scope of the fact sheet

This factsheet introduces a pre-posterior decision making framework for quantifying the value of monitoring of buildings exposed to seismic risk. In this context, methods for automatic damage detection, joint utilisation of monitoring and visual inspection data, and modelling of earthquake consequences are discussed.

Abstract

Adoption of a monitoring system should be based on sound appraisal of the likely economic benefits of such decisions. These benefits can be quantified in terms of the reduction of the risks posed by the failure of structural system to be monitored versus the cost of monitoring. Yet, there seems to be dearth of appropriate tools for such decisions. This factsheet discusses a framework for rationalising the adoption of monitoring for buildings subjected to seismic risks. This is cast in the theoretical rigour of the pre-posterior decision analysis. Two types of monitoring are considered, namely for quick appraisal of a single building state and damage following a seismic event, and for updating the seismic risk for a building or a larger stock of structures through long term monitoring. In the context of quick post-event condition assessment, methods for automatic damage detection and joint utilisation of monitoring and visual inspection data are considered from a point of view of how they can be used in the pre-posterior analysis. Modelling of the various consequences or costs of earthquakes, including damage to structural and non-structural components and content, human fatalities, injuries and trauma, and loss of building function are also discussed as an indispensable ingredient of modelling risk. Two numerical examples are included to illustrate the theory.

Basis / theory / methods

The theoretical framework is that of the pre-posterior analysis.

Application areas

The concepts presented in this factsheet are applicable to the management of risks to buildings located in areas of significant seismicity.

Critical appraisal

This factsheet is an exposition of a pre-posterior analysis theory applied to the problem of adoption of monitoring for buildings exposed to seismic risk. The pre-posterior analysis is a sound, well established and rigorous theoretical framework. Here, to the best of authors' knowledge, it is applied for the first time to the problem of quantifying the value of information from seismic monitoring of buildings. Aspects of integrating automatic damage detection and visual inspection results and earthquake consequence modelling are also discussed but future research on real buildings should be further pursued to test robustly the theory proposed.

Leading research communities / leading application sectors

This factsheet addresses the needs of the structural health monitoring research community and potential users of the technology interested and having stake in its applications to buildings exposed to risks from earthquakes.

1 Introduction

This factsheet proposes pre-posterior analysis frameworks for quantifying the value of monitoring and inspections in buildings subjected to seismic hazards and elaborates on its constituent parts such as methods for damage detection using sensor and visual inspection data and estimating the consequences and costs of various decision scenarios. The notion of monitoring is not confined to sensors installed directly on the building but also includes borehole sensors located near the building and sensors at the foundation level (which can help identifying the seismic excitation to the structure), and even sensors from wide-area seismic monitoring arrays that can help to better understand the behaviour of nearby faults and seismic wave attenuation characteristics. This is schematically shown in Fig. 1, where examples of different types of seismic sensing arrays and data collection approaches are indicated.

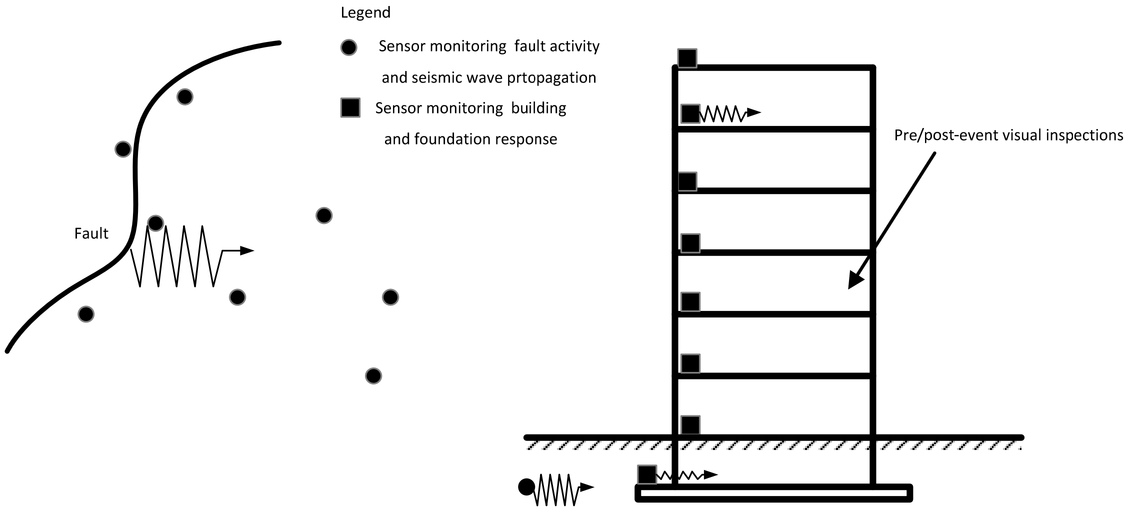


Figure 1: Collecting data via seismic monitoring and inspections.

While making a decision, a number of choices available compete. These choices include ‘do nothing’, invest in different types of SHM technologies or systems with associated performance characteristics, invest in enhanced pre/post-earthquake visual inspections (e.g. similar to San Francisco’s Building Occupancy Resumption Programme (City and County of San Francisco 2016), invest in seismic retrofit, and others; some choices may be combinations of the aforementioned.

There are two types of using seismic monitoring data considered in this study. The first type is concerned with detecting damage quickly after a strong motion event to decide if the building has to be evacuated or can continue normal operations. The second type uses monitoring data, typically collected over long periods of time to capture many events of varying intensity, to update estimates of seismic hazard and structural vulnerabilities, to be able to better predict seismic risk to the structure. Note that the two types of monitoring may use the same physical hardware. It is also possible to combine the two types of monitoring data usage, though this is not considered in this paper.

2. Type 1 seismic monitoring: Quick post-event damage detection

Suppose the stakeholders in the building are to decide if they want to adopt a monitoring system that will detect damage to the building struck by a strong earthquake. Depending on the output from the monitoring system the building will be either evacuated or normal, uninterrupted building usage will continue. The different scenarios entail different consequences, expressed here as costs. It is likely that not all interested parties will be exposed to all the consequences to the same degree, but in this general explanation of the decision framework we do not make such differentiations. We will use the pre-posterior analysis framework (Raiffa and Schlaifer 1961) to identify the optimal decision.

The possible choices (decisions or acts) and outcomes and states of nature for deciding whether to adopt of Type 1 monitoring are shown in Table 1. The set of prior probabilities applicable to the problem are summarised in Tables 2 and 3. The prior probabilities of damage being sustained (Table 2) can be obtained via seismic hazard and structural vulnerability analysis (Kappos et al. 2006, Singhal and Kiremidjian 1996). The likelihoods of damage being detected if it actually occurred and vice versa can be evaluated in many ways including numerical analysis, laboratory experimentation and full scale experimentation and observations (the latter option is currently very limited, if impractical, due to the general dearth of monitoring data from full scale structures that have actually been damaged or tested to damage). The various costs assumed to be involved in the decision making are summarised in Table 4.

Figure 2 shows the decision tree for the problem at hand. In the decision tree, there are posterior probabilities indicated for the actual damage sustained **DS** given the damage detection outcome **DD** from the monitoring system. These can be calculated using Bayes' theorem as shown in Table 5. These calculations also yield the probabilities of the monitoring system indicating damage DD_1 or not DD_0.

The optimal decision is the one that minimizes the overall expected cost C:

$$MO_{opt} = \min_{MO_i \in \mathbf{MO}} E_{DD} \min_{EV_k \in \mathbf{EV}} E_{DS|DD} \left[C\left(MO_i, DD_j, EV_k, DS_l\right)\right] \tag{1}$$

over all possible sequences of choices and chance outcomes (MO, DD, EV, DS) from the intersection of spaces **MO×DD×EV×DS**. (We assume a risk neutral behaviour but by defining a different utility risk aversion or loving can easily be accommodated.)

Table 1: Choices, their outcomes and states of nature in Type 1 monitoring.

Decision/random event	Options/outcomes/states of nature	Interpretation
Adopt monitoring system, **MO**	MO_0 MO_1	Do not adopt monitoring Adopt monitoring
Damage detected by monitoring system, **DD**	DD_0 DD_1	Damage not detected Damage detected
Evacuate building, **EV**	EV_0 EV_1	Do not evacuate Evacuate
Damage actually sustained, **DS**	DS_0 DS_1	Damage not sustained Damage sustained

Table 2: Prior probabilities of damage to be sustained **DS** by the building.

DS_0	DS_1
p_{DS0}	p_{DS1}

Table 3: Likelihood probabilities of damage detection **DD** by a monitoring system.

	DD_0	DD_1
DS_0	$p_{DD0\|DS0}$	$p_{DD1\|DS0}$
DS_1	$p_{DD0\|DS1}$	$p_{DS1\|DS1}$

Table 4: Costs.

Cost type	Notation
Cost of monitoring system design, hardware, software, integration, installation, maintenance, data storage and data analysis	C_{monit}
Cost of structural, non-structural and content damage	C_{damage}
Costs as result of consequences to humans (casualties, injuries and trauma)	$C_{casualty}$
Cost of interruption to business and occupancy	$C_{interrupt}$

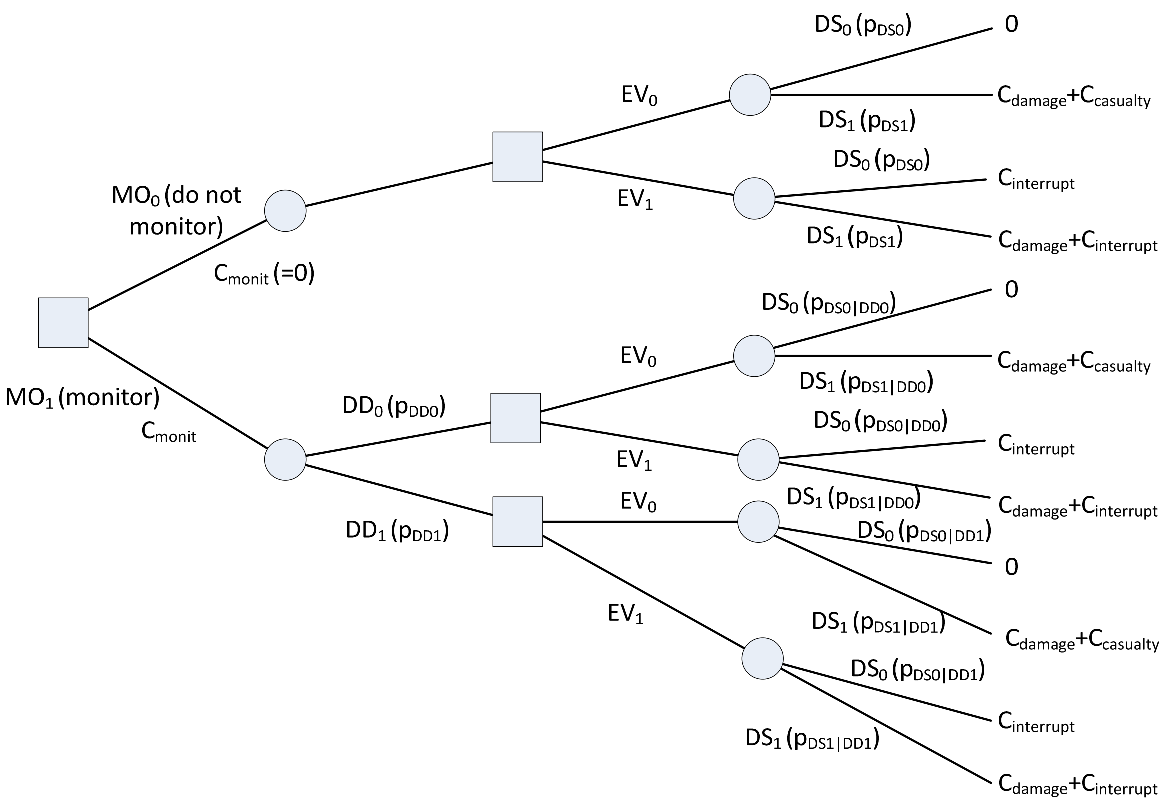


Figure 2: Decision tree for adoption of Type 1 monitoring system.

Table 5: Calculation of posterior probabilities.

State of nature	Prior proba-bilities	Likelihood proba-bilities	Intersection probability	Posterior probability
DS_0	p_{DS0}	$p_{DD0\|DS0}$	$p_{DS0}p_{DD0\|DS0}$	$p_{DS0\|DD0}=p_{DS0}p_{DD0\|DS0}/p_{DD0}$
DS_1	p_{DS1}	$p_{DD0\|DS1}$	$p_{DS1}p_{DD0\|DS1}$	$p_{DS1\|DD0}=p_{DS1}p_{DD0\|DS1}/p_{DD0}$
			$p_{DD0}=p_{DS0}p_{DD0\|DS0}+p_{DS1}p_{DD0\|DS1}$	
DS_0	p_{DS0}	$p_{DD1\|DS0}$	$p_{DS0}p_{DD1\|DS0}$	$p_{DS0\|DD1}=p_{DS0}p_{DD1\|DS0}/p_{DD1}$
DS_1	p_{DS1}	$p_{DD1\|DS1}$	$p_{DS1}p_{DD1\|DS1}$	$p_{DS1\|DD1}=p_{DS1}p_{DD1\|DS1}/p_{DD1}$
			$p_{DD1}=p_{DS0}p_{DD1\|DS0}+p_{DS1}p_{DD1\|DS1}$	

2.1. Example 1

Consider a selection of buildings with different prior probabilities p_{DS1} of sustaining damage in an earthquake ranging from 1% through to 99%. The constituent costs of different chance outcomes (expressed in non-dimensional units) are $C_{damage}=2\times10^5$, $C_{casualty}=1\times10^6$ and $C_{interrupt}=1\times10^5$. Several monitoring systems are considered which have different likelihood probabilities of correct damage detection as shown in Table 6, where the probability of correct indication p_l ranges between 50% and 99%. The former value represents a very poorly performing system which gives purely random indications, whereas the latter a system that is very accurate. It is assumed that the cost of accuracy increases exponentially with the probability of correct indication p_l as the proportion of C_{damage} starting with 0.1% for p_l=50% and ending with 5% for p_l=99%, respectively. This is shown in Fig. 3.

Table 6: Likelihood probabilities of damage detection by monitoring system used in Example 1.

	DD_0	DD_1
DS_0	p_l	$1-p_l$
DS_1	$1-p_l$	p_l

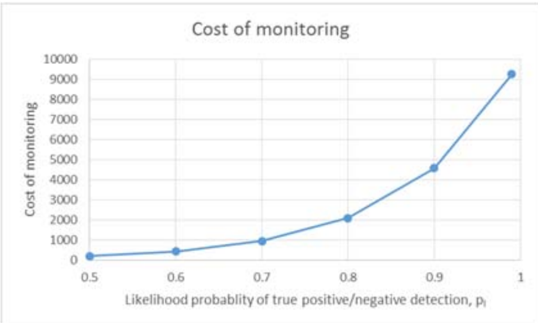


Figure 3: Cost of monitoring vs. likelihood of correct damage detection used in Example 1.

Figure 4 shows the simulation results as the ratios of the total expected cost of decisions to use different monitoring systems to the expected cost of 'do nothing'. It can be seen that for buildings with low prior damage probabilities, e.g. 1%, the additional information provided by monitoring is not able to reduce the overall expected cost. This is because the monitoring information for this case will only provide some reassurance for the optimal prior decision that the optimal action is not to evacuate the building in the event of an earthquake (EV_0) (because of the low risk of casualties and high cost of operational interruption), while still costing money. Similarly, for high prior damage probabilities, e.g. 99%, the additional information from monitoring does not change the prior optimal decision to evacuate (EV_1), because of the high risk of casualties. Where monitoring is useful is the intermediate range of prior damage probabilities. There, the additional information from monitoring can identify cheaper options. For example, for a prior damage probability of 20%, the additional information from monitoring systems with likelihood of correct detection not less than 70% will enable making decisions about evacuation based on the outcomes of monitoring leading to the reduced overall expected costs. All the observations and conclusions in this simple illustrative example depend, as a matter of course, on the assumed costs of each decision and chance outcome.

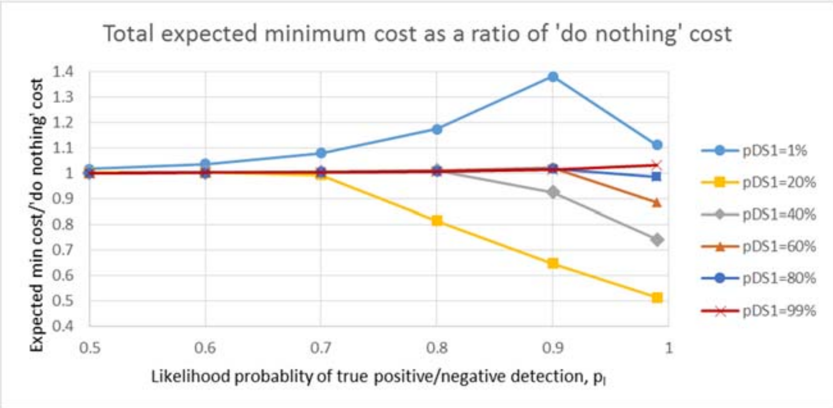


Figure 4: Comparison of total expected cost of decisions to use different monitoring systems for buildings with different prior seismic damage probabilities in Example 1.

3. Type 2 seismic monitoring: Updating structural risk profile

Suppose the building stakeholders are now contemplating to use monitoring data to update the seismic risk to their building via quantifying better the seismic hazards and vulnerabilities faced by the building. If risk can be demonstrated to be lower, they can, for example, ask for the insurance premium on the building to be lowered. Here, it can be useful to also use wider seismic arrays, e.g. for monitoring a nearby fault. (In this case it may be that a group of owners of buildings, or perhaps a local council, or even a government body, will fund and oversee such an endeavour for the common or wider benefit.) The pre-posterior framework for such and analysis is similar to Type 1 monitoring and only the most important differences are explained below. Table 7 lists the decision options and chance outcomes – the only difference compared to Type 1 monitoring (Table 1) is that the damage detection space **DD** is replaced by the space of new estimates of damage probability **NE** with three possible outcomes. The decision tree for Type 2 seismic monitoring is shown in Figure 5.

4. Methods for automatic damage detection for Type 1 monitoring

Damage detection systems are usually based on the detection of changes in a damage feature, i.e. a parameter which is sensitive to damage. An important family of damage features is the one including parameters that can be retrieved from the vibratory structural responses. A number of different vibration-based features have been proposed in literature in the last 30 years and comprehensive surveys are reported in Fan and Qiao (2011), Carden and Fanning (2004), and Sohn et al. (2003). Many of them are based on modal frequencies, modal or operational shapes and their derivatives (rotations, flexibilities and curvatures). Natural frequencies have been widely used for damage detection purposes, i.e. to assess the existence of damage, since they can be measured from a very limited number of sensors and are less contaminated by noise than modal or operational shapes. One of the major problems with the use of modal frequencies for damage

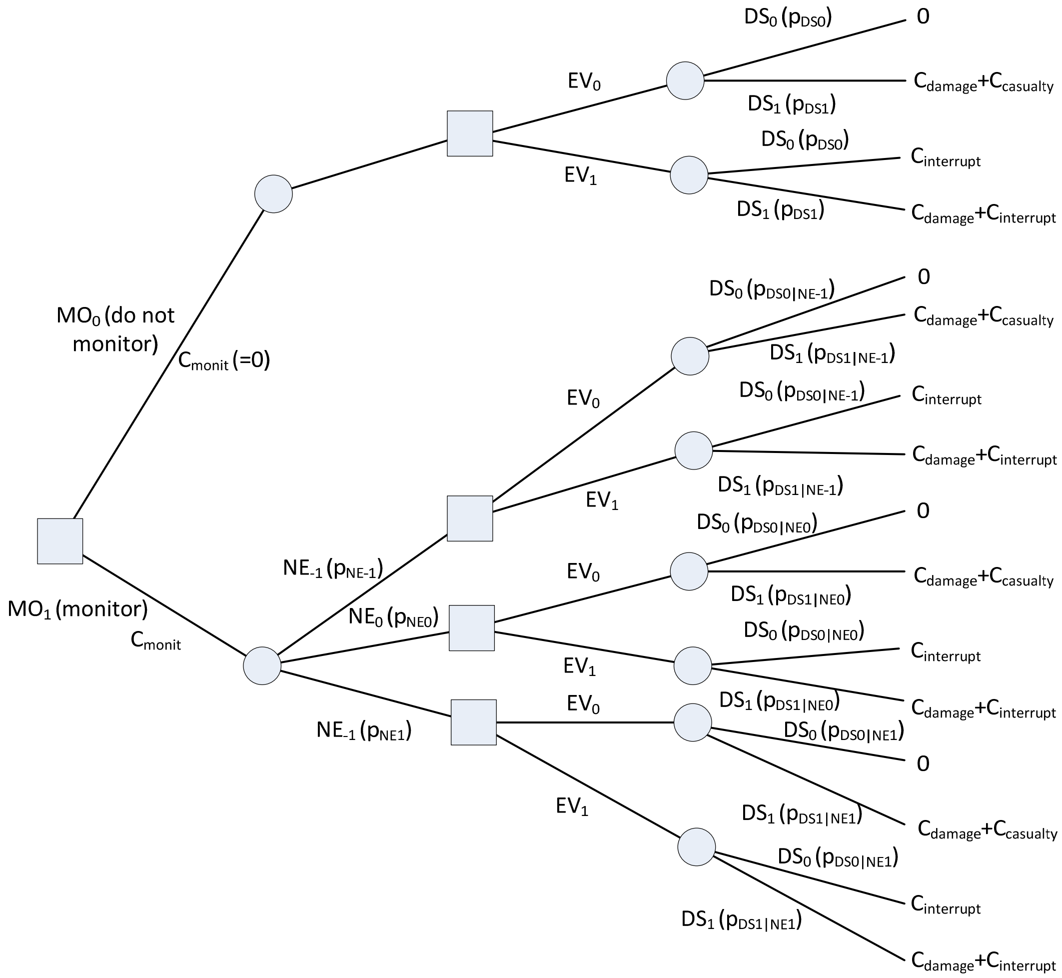


Figure 5: Decision tree for adoption of Type 2 monitoring system.

Table 7: Choices, their outcomes and states of nature in Type 2 monitoring.

Decision/random event	Options/outcomes/states of nature	Interpretation
Adopt monitoring system, **MO**	MO_0 MO_1	Do not adopt Adopt
New estimates of damage probability from monitoring data, **NE**	NE_{-1} NE_0 NE_1	Damage less probable than previously thought Damage equally probably than previously thought Damage more probable than previously thought
Evacuate building, **EV**	EV_0 EV_1	Do not evacuate Evacuate
Damage actually sustained, **DS**	DS_0 DS_1	Damage not sustained Damage sustained

detection is the possible influence of varying environmental and operational conditions pointed out by several authors (Alampalli 2000, Cawley 1997, Limongelli 2010, Roberts and Pearson 1998, Rohrmann et al. 1999, Sohn 2007, Williams and Messina 1999, Limongelli et al. 2016). Sources such as temperature, moisture, nonlinear behaviour, soil-structure interaction, noise in recorded data, unaccounted for excitation sources such as traffic and others, can induce variations in the damage feature even if no damage occurs leading to false alarms. Conversely, variations in the damage feature due to genuine damage may be erroneously attributed to the aforementioned sources leading to missing correct alarms. The variability of the damage features with environmental and operational conditions has thus to be taken into account in the damage assessment procedures. To this effect, two main approaches are proposed in literature. The first one is based on techniques able to remove the effect of the environment from the features chosen to indicate the existence and location of damage (Peeters and De Roeck, 2000, Kullaa 2004). The second approach is based on the use of damage detecting features that are scarcely affected by changes in the environmental conditions but strongly affected by damage (Deraemaeker and Preumont 2006, Limongelli 2010). In any case, even when using the second type of features, the statistical variability of the damage feature must be properly taken into account in order to make the damage assessment technique robust for low extents of damage that may induce variations in the damage feature of the same order of magnitude of the environmental and/or operational sources. This is particularly important in the realm of the estimation of the efficacy of a monitoring system aiming to assess if it is worth to install it on a structure.

In order to cast the use of damage detection techniques in the probabilistic pre-posterior framework outlined in the previous sections, the conditional and total probabilities included in the decision tree in Fig. 2 and in Tables 3 and 4 are defined herein with reference to probability distribution function of a damage detecting feature. In Fig. 6, the distributions of a damage feature respectively in the undamaged, $f_{d/DD0}$, and damaged, $f_{d/DD1}$, configurations are shown. In this case, damage induces an increase in the damage feature, hence a shift of the distribution towards higher values.

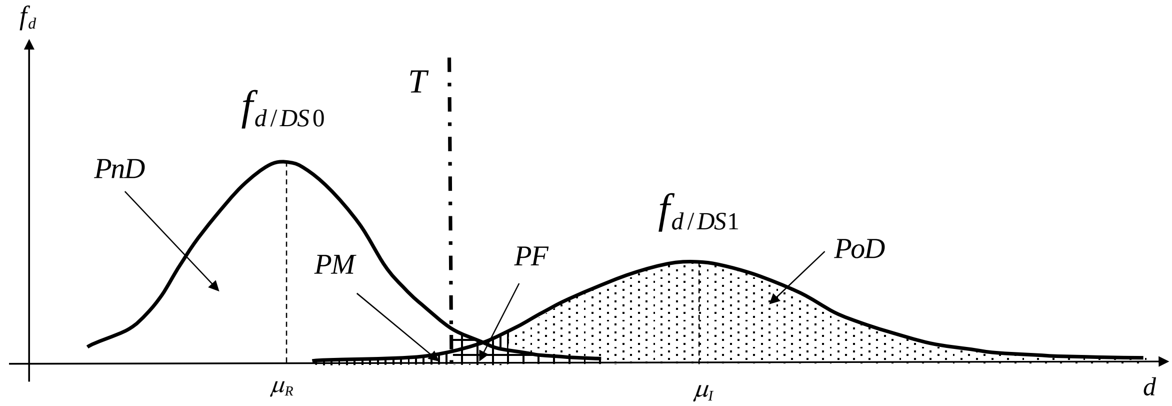


Figure 6: Distributions in the undamaged ($f_{d/DS0}$) and in the damaged ($f_{d/DS1}$) configurations

Depending on the type of monitoring system installed, different situations may occur:

- Permanent (long term) monitoring: network of sensors permanently installed on the structure allowing to estimate both $f_{d/DS0}$ and $f_{d/DS1}$, assuming damaging events occur within the monitoring window.
- Periodic monitoring: network of sensors installed for a limited period of time on the original structure allowing to estimate $f_{d/DS0}$ and then removed. Further monitoring carried out in emergency situations (e.g. after a possible damaging events such as an earthquake) do not allow the full estimation of $f_{d/DS1}$ because of limited data.

- Short term monitoring: A very limited (just one in some cases) number of tests carried out in the reference and in a possible damaged configuration. In this case neither $f_{d/DS0}$ nor $f_{d/DS1}$ can be properly estimated.

In the cases of periodic or permanent monitoring, the estimation of $f_{d/DS1}$ (and also of $f_{d/DS0}$ for short term monitoring) should be carried out using numerical models or using a model of the distributions themselves.

In the framework for the quantification of the value of a monitoring system to be installed, the probability distribution functions cannot be estimated on the structure to be monitored since the monitoring system is not yet installed. Their estimation has to be carried out based on numerical models or using statistical models of the distributions themselves which is a challenging task due to the difficulty in reliably simulating both the structural nonlinear behaviour and the variability of the damage feature due the random sources such as temperature. This step is, however indispensable if we are to quantify the value of future monitoring information.

If a decision has to be taken regarding the effectiveness of the monitoring system, the minimum expected cost based on pre-posterior decision analysis (corresponding to the branch MO_1 in Fig. 2) can be calculated and compared to the cost based on the prior decision analysis (corresponding to the branch MO_0 in Fig. 2). The difference between the two costs then gives the maximum amount one may be willing to pay for a monitoring system.

In this factsheet we consider a simplified situation that only two states of nature exist, i.e. DS_0 - the structure is not damaged, and DS_1 - the structure is damaged. With reference to the decision tree in Fig. 2 and to Table 5, the prior probabilities p_{DS1} and p_{DS0} and the likelihood functions of damage being detected if it actually occurred and vice versa need to be estimated. The prior probabilities p_{DS1} and $p_{DS0} = 1 - p_{DS1}$ can be estimated using fragility curves that express the probability that a structure will sustain different degrees of damage at given ground motion levels (Kappos et al. 2006, Singhal & Kiremidjian 1996). A fragility curve for a particular damage state is a plot of the conditional probabilities $p(DS_{ik})$ of exceeding that damage state at various levels of ground motion a_k:

$$p(DS_{ik}) = p\left[D \geq d_i \middle| A = a_k \right] \qquad (2)$$

The value of the damage parameter D at which the i-th damage state is attained in the fragility curve is denoted by d_i. Parameter A describes the severity of the ground motion (e.g. peak ground acceleration) and a_k is the value of A corresponding to the limit d_k in the fragility curve. From Eq. (2), using the fragility curve the prior probability of damage p_{DS1} can be calculated together with the prior probability of no damage $p_{DS0} = 1 - p_{DS1}$ as functions of the seismic hazard parameter A.

Several definitions have been proposed in literature for the parameter D. Most of them are based on ductility ratio and/or dissipated energy such as the Park and Ang index (Park and Ang 1985) or on the interstory drift (Krawinkler and Miranda 2004); others are defined as direct loss index that is the ratio of the repair cost to the replacement cost (Kappos et al. 2006).

In order to calculate the probabilities p_{DD1} and p_{DD0} in figure 2 and to table 5, the conditional probabilities $p_{DD1|DS1}$, $p_{DD1|DS0}$, $p_{DD0|DS1}$ and $p_{DD0|DS0}$ are needed. These are the likelihood probabilities that damage is declared (not declared) by the monitoring system given damage actually exists (or not exist), and they can be estimated based on the probability distribution functions of the damage feature. Specifically:

- $p_{DD1|DS1}$ is the probability of detection (PoD), i.e. the probability that the damage detection algorithm indicates a damage given the damage actually exist,
- $p_{DD1|DS0}$ is the probability of a false alarm (PF), i.e. the probability that the damage detection algorithm erroneously indicates a damage that does not exist,
- $p_{DD0|DS1}$ is the probability of missing alarm (PM), i.e. the probability that the damage detection algorithm does not indicate a damage when the damage actually exist, and
- $p_{DD0|DS0}$ is the probability of no detection (PnD=1-PF) that is the probability that the damage detection algorithm correctly does not indicates a damage when it does not exist.

It is noted that the outcomes DD_0 (no damage) and DD_1 (damage) from the monitoring system require that a threshold is defined, so that if the value of the damage feature is below the threshold *T* (see Fig. 6), the outcome will be DD_0, otherwise it will be DD_1. The values for PoD, PnD, PF and PM are all functions of the value chosen for the threshold *T*. The threshold is usually defined based on a trade-off between PM and PF, i.e. between the user's risk that for a damaged building the necessary intervention is not carried out thus jeopardizing the lives of the building's users, $C_{casualty}$ in Fig. 2, and the owner's risk that for an undamaged structure an unnecessary, but costly, evacuation is carried out resulting in interruption to occupancy and business, $C_{interrupt}$.

4.1. Example 2

In the following an example is given for the estimation of the probabilities p_{DD1} and p_{DD0}. Assume that the prior probabilities of damage, retrieved from the fragility curve of the considered structure, as a function of the seismic hazard *A*, are $p_{DS1} = 70\%$ and $p_{DS0} = 30\%$, respectively. Using a numerical model, capable of simulating the non-linear behaviour of the structure and all the sources of random variations of the damage feature, one can calculate the probability distributions of the damage feature $f_{d/DD0}$ (for the undamaged structure) and $f_{d/DD1}$ (for the structure damaged e.g. by an earthquake of severity a_1). Herein, for the sake of simplicity it will be assumed that the damage feature is the fundamental period of the structure and that the two likelihood functions of this feature in the undamaged and in the damaged configurations are described by Gaussian distributions. The probability densities assumed for the two distributions are reported in Table 8 and in Fig. 7.

In Fig. 8, the variations of the conditional probabilities with the value of the threshold *T* are reported. As already remarked, the probability of false and missing alarms follow opposite trends as the probability of detection PoD and of no detection PnD: at the increase of the threshold the PF decreases but the PM increases.

Table 8: Parameters of damage feature probability density functions used in Example 2.

	DS_0	DS_1
Mean	1.5s	3.0s
Standard deviation	0.4s	1.0s

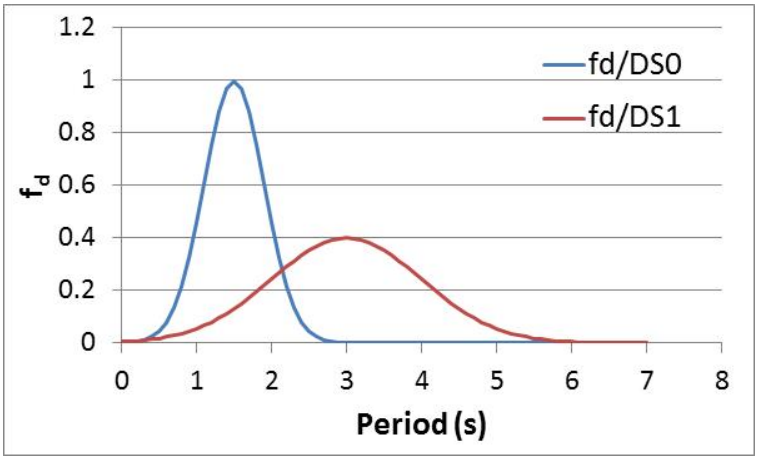


Figure 7: Damage feature probability density functions used in Example 2.

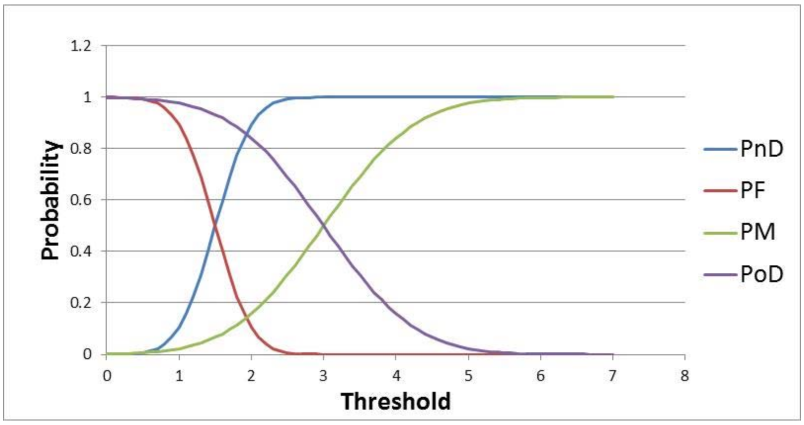


Figure 8: Variation of conditional probabilities PnD, PF, PM, PoD with threshold *T*.

A possible choice for the threshold can be the value that results in equal costs for the false and missing alarms, i.e.:

$$PM \times \left(C_{damage} + C_{casualty}\right) = PF \times C_{interrupt} \tag{3}$$

Hence, considering the values assumed in Example 1, $C_{damage}=2\times10^5$, $C_{casualty}=1\times10^6$ and $C_{interrupt}=1\times10^5$, this choice of the threshold corresponds to the following ratio of PM to PF:

$$\frac{PM}{PF} = \frac{C_{interrupt}}{\left(C_{damage} + C_{casualty}\right)} = \frac{1\times10^5}{\left(2\times10^5 + 1\times10^6\right)} = 0.0833 \tag{4}$$

The conditional probabilities corresponding to the so defined threshold are reported in Table 9.

Table 9: Mean and standard deviation of the likelihood functions of the damage feature.

PnD	PF	PM	PoD
0.377	0.623	0.053	0.947

The values of the probabilities of detection, p_{DD1}, and of no detection, p_{DD0}, are thus:

$$p_{DD0} = p_{DD0|DS1}p_{DS1} + p_{DD0|DS0}p_{DS0} = 0.052 \times 0.7 + 0.377 \times 0.3 = 0.15 \tag{5}$$

$$p_{DD1} = p_{DD1|DS1}p_{DS1} + p_{DD1|DS0}p_{DS0} = 0.947 \times 0.7 + 0.622 \times 0.3 = 0.85 \tag{6}$$

5. Joint utilization of inspection and health monitoring data

Evaluation of post-earthquake safety of damaged buildings requires reliable prediction of its likely performance during the service life. In achieving this goal, the damage information obtained from the post-earthquake damage inspections has considerable potential in supplementing the damage information obtained from seismic monitoring. In order to predict the building performance with sufficient accuracy, a reliable analytical model of the structure needs to be developed and the expected seismic hazard at the site of the building needs to be estimated. This requires establishing an effective analytical model which captures the essential response characteristics of the considered building.

In order to establish suitable analytical models, accurate and precise information on the building of interest is needed. However, very often actual material properties cannot be determined precisely and they can only be estimated with significant uncertainty. Moreover, several idealizations and assumptions need to be introduced to reduce the problem to a manageable level of complexity. These simplifications may lead to differences between the actual behaviour of the building and that obtained using the utilized analytical model. Lack of precise information and reliance on simplified models unavoidably results in considerable uncertainty of the predicted response. In order to represent the effects of this uncertainty on the predicted performance, the expected variability of the performance must also be taken into account in the assessment of important buildings. This is usually achieved by taking into account potential variations in the model parameters and utilizing alternative modelling strategies.

In the envisioned framework, a set of alternative analytical models are established for the building that is under consideration. Subsequently, from this entire set of models the specific subset of models which better represent the actual seismic response characteristics of the considered structure are identified. Using the identified models, the expected performance of the building during its remaining service life is predicted and the risk associated with the structure is evaluated.

As the first step, the main uncertain parameters (P_1, P_2, …, P_{Np}) that influence the estimated risk are identified. These parameters may be related to material strengths, strain limits, boundary conditions, etc. Probability distribution functions, f_{Pi}, are established for the considered N_p parameters using the available literature (e.g. JCSS 2001). For each parameter, N_m realizations are generated using the distributions f_{Pi}. As a result, N_m candidate models are generated. This step is similar to the plain Monte Carlo simulation. For an individual model (i.e. model-i) from amongst the entire set of generated models, all parameter values are contained in the vector $\boldsymbol{m}_i$. Before any inspection or monitoring data is considered, all models ($\mathbf{m}_1$, $\mathbf{m}_2$,…, $\mathbf{m}_{Nm}$) have an equal likelihood of being the most representative. Hence, this likelihood $P[\mathbf{M}=\mathbf{m}_i]$ for $\mathbf{m}_i$ is defined as:

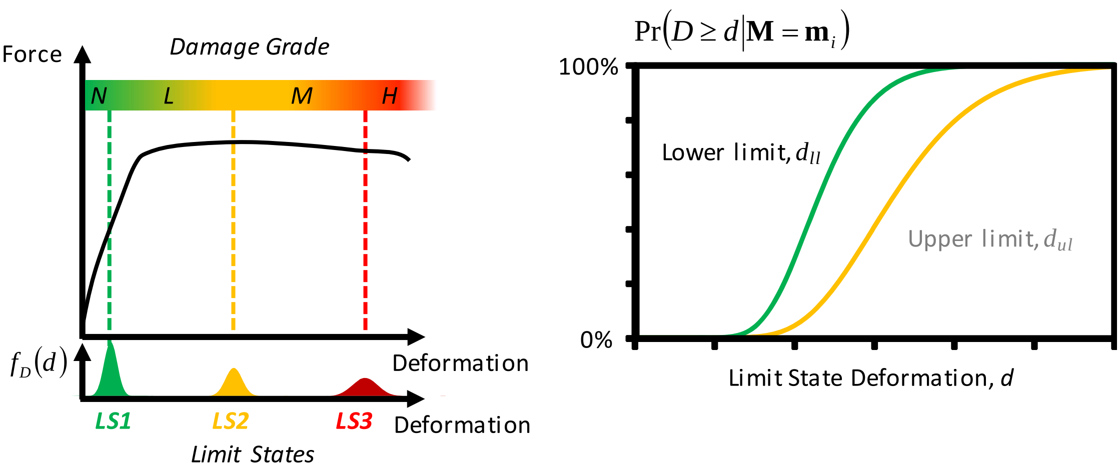
$$P\left[\mathbf{M} = \mathbf{m}_i\right] = \frac{1}{N_m} \tag{7}$$

This likelihood represents the prior likelihood for $\mathbf{m}_i$. Evaluation of model likelihood conditional on the inspection and monitoring data, is presented in the following.

Damage inspection involves identifying the damage grades of components and determining the related damage mechanism. Damage grades are determined based on observed visual indicators (e.g. spalling of cover, cracking, and reinforcement bar rupture) (Fig. 9). When a structural component is observed to have sustained a specific grade of damage, it may be inferred that during the earthquake the component had deformed beyond the deformation limit, d_{ll}, which corresponds to the lower limit of the identified grade (Fig. 10a). Moreover, from the observation of the level of sustained damage it can also be inferred that upper deformation limit, d_{ul}, for the identified damage grade was not exceeded during the earthquake. Limit state displacements corresponding to the lower and upper bounds can be estimated probabilistically for each model realization (e.g. $\mathbf{m}_i$) using the existing structural member performance prediction models (Fardis and Biskinis 2003, Berry and Eberhard 2003).

a) b) c)

Figure 9: Examples of indicators observed during post-earthquake inspection: a) cracking of concrete, b) buckling of reinforcement, and c) anchorage pull-out (Fardis et al. 2008, Yazgan et al. 2012)



(a) (b)

Figure 10: Definition of damage grades and corresponding limit states: a) force-deformation behaviour, and b) cumulative probability distributions $P[D \geq d|\mathbf{M}=\mathbf{m}_i]$ of the limit state distributions conditional on model $\mathbf{m}_i$.

Taking into account the observation of component deformation D has exceeded the lower bound limit state displacement d_{ll}, the posterior likelihood $P[\mathbf{M}=\mathbf{m}_i|D \geq d_{ll}]$ for model $\mathbf{m}_i$ can be evaluated as:

$$P\left[\mathbf{M}=\mathbf{m}_i \left| D \geq d_{ll} \right.\right] = \frac{P\left[D \geq d_{ll} \left| \mathbf{M}=\mathbf{m}_i \right.\right] P\left[\mathbf{M}=\mathbf{m}_i\right]}{\sum_{j=1}^{N_m} P\left[D \geq d_{ll} \left| \mathbf{M}=\mathbf{m}_j \right.\right] P\left[\mathbf{M}=\mathbf{m}_j\right]} \tag{8}$$

Conditional probabilities $P[D \geq d_{ll} | \mathbf{M}=\mathbf{m}_i]$ can evaluated using the component fragility models (Fig. 10b), which are frequently utilized in performance-based seismic design of structures. Subsequently, the resulting probabilities can be further updated by taking into account the fact that the upper limit state deformation d_{ul} was not exceeded as follows:

$$P\left[\mathbf{M}=\mathbf{m}_i \left| D < d_{ul} \cap D \geq d_{ll} \right.\right] = \frac{P\left[D < d_{ul} \left| \mathbf{M}=\mathbf{m}_i \right.\right] P\left[\mathbf{M}=\mathbf{m}_i \left| D \geq d_{ll} \right.\right]}{\sum_{j=1}^{N_m} P\left[D < d_{ul} \left| \mathbf{M}=\mathbf{m}_j \right.\right] P\left[\mathbf{M}=\mathbf{m}_j \left| D \geq d_{ll} \right.\right]} \tag{9}$$

The conditional probability $P[\mathbf{M}=\mathbf{m}_i | D \geq d_{ll} \cap D < d_{ul}]$ represents the likelihood estimated for model $\boldsymbol{m}_i$ by taking into account that damage grade observed for the structural component. Equations (8) and (9) correspond to the case of considering damage observed in a single component. In order to consider an entire set of inspected components, these equations may be evaluated repetitively. In each repetition, damage grade observation related to a different structural member will be taken into account.

Joint set of all damage grade observations (e.g. $D_1 \geq d_{ll} \cap D_2 < d_{ul} \cap \ldots$) for the entire set of inspected components can be defined as the inspection event I and formulated as follows:

$$I = \left\{ D < d_{ul} \cap D \geq d_{ll} \cap \ldots \right\} \tag{10}$$

When the procedure presented above is applied, the posterior probability $P[\mathbf{M}=\mathbf{m}_i | I]$ for model $\boldsymbol{m}_i$ is obtained.

Seismic monitoring of a building may provide critical information about the stiffness, vibration mode shapes, and the damping characteristics. In the following, only the case for utilizing the stiffness value obtained from the monitoring data is presented. Other types of information obtained from the monitoring data may also be utilized through a straightforward modification of the presented equations. When the stiffness of the structure has been identified to be equal to a specific value k_h through the use of health monitoring data, the posterior probability $P[\mathbf{M}=\mathbf{m}_i | K=k_h \cap I]$ for model-i can be evaluated as follows:

$$P\left[\mathbf{M}=\mathbf{m}_i \left| K = k_h \cap I \right.\right] = \frac{P\left[K = k_h \left| \mathbf{M}=\mathbf{m}_i \right.\right] P\left[\mathbf{M}=\mathbf{m}_i \left| I \right.\right]}{\sum_{j=1}^{Nm} P\left[K = k_h \left| \mathbf{M}=\mathbf{m}_j \right.\right] P\left[\mathbf{M}=\mathbf{m}_j \left| I \right.\right]} \tag{11}$$

In Eq. (11), K is the random variable representing the stiffness of the structure and k_h is the specific value of stiffness determined based on health monitoring data. In order to take into account other parameters (e.g. mode shape and damping), evaluation of Eq. (11) should be repeated by further updating the model likelihoods $P[\mathbf{M}=\mathbf{m}_i | \ldots]$ and considering additional building specific observation as an additional conditioning information in each repetition. When introducing each new conditioning information, potential correlations among different observations should be avoided. If necessary, variable transformations should be introduced to avoid such issues.

Similar to the joint event defined above for the inspection results, the joint set of observations (e.g. $K_1=k_{h1}$, $K_2=k_{h2}$) derived from structural health monitoring data can be represented as the event H, as follows:

$$H = \{K_1 = k_{h1} \cap K_2 = k_{h2} \ldots\} \tag{12}$$

From the sequential and repetitive evaluation of Eqs. (8), (9) and (11) the posterior probability $P[\mathbf{M}=\mathbf{m}_i|H \cap I]$ for model $\mathbf{m}_i$ which is jointly conditioned on the inspection data, I, and health monitoring data, H, can be evaluated.

6. Modelling consequences and costs of seismic damage to buildings

The motivation to use seismic monitoring systems is to reduce the likely consequences, or risk, of earthquake hazard exposure to the building. This section is devoted to modelling such consequences that can in turn be used in making decisions about the adoption of a monitoring system. While the seismic damage consequences come in many various forms, which can in turn be measured in many ways, there is a need to be able to combine them and compare. While there are practical difficulties in doing so, and there will always be an ethical dilemma if a monetary value can be assigned to human life, the cost is practically the only unifying measure we will likely ever have (Kanda and Shah 1997). Hence, the cost is used herein to express all the consequences quantitatively. It is always important to account for the discount rate of money when using past monetary figures or making predictions into the future, as is converting to a common currency using the conversion rate at the time of occurrence (Janssens et al. 2009).

Consequences of exposure to a hazard are often divided into the direct and indirect consequences (JCSS 2008). In the context of structural systems, the direct consequences are often associated with local, component level structural damage (Sorensen et al. 2009). The indirect consequences take their roots in the local damage but progress to affect a larger part of a structure, perhaps leading to its total collapse, its occupants, functionality and even surroundings. An example could be severe seismic damage to a weak storey (a direct consequence) that subsequently leads to the whole building collapsing, casualties and injuries (indirect consequences). The closely related concept is that of robustness: a robust system is one in which the direct damage does not lead to disproportional indirect consequences (Baker et al. 2008). It is often ambiguous where the direct consequences end and indirect begin. This depends on the context but should always be specified for clear risk analysis. In the context of using seismic monitoring we will divide consequences into immediate and delayed. The immediate consequences are those that cannot be avoided using monitoring, whereas delayed consequences are those that can be influenced (avoided or mitigated) using monitoring information. For example, immediate seismic structural damage and resulting casualties cannot be avoided using a damage detection system, however, further casualties and injuries in a building weakened by the main shock that subsequently falls in an aftershock can be avoided if the structure is evacuated based on the information from a damage detection system. In that sense, monitoring is a tool that can be used to enhance robustness. Also, the proposed classification of consequences must take into account the time scales at which the monitoring system operates and decisions are made: e.g. if a decision to evacuate the building takes long, the consequences of a collapse not immediately during or after the main shock may need to be included in the immediate costs.

Janssens et al. (2009) discuss general and broad consequences of building failures, while Kanda and Shah (1997) examine more specifically consequences of seismic failures to buildings including residential, office, retail, hospitals, power plants and others. We used primarily these two sources to select the relevant consequences and compile the list shown in Table 9. In composing the list, we used our aforementioned classification into the immediate and delayed consequences. We focused on consequences most relevant for large office or residential buildings or structures of mixed usage. In the following sections, modelling of the cost of each of the main categories (structural and content damage, human consequences and loss of function) are described in some detail.

Table 10. Immediate and delayed consequences of building exposure to seismic hazard.

Category	Immediate consequences	Delayed consequences
Structure and content	Immediate damage to structure (repair or rebuild)	Delayed damage to structure (repair or rebuild) because the structure was not repaired in time for aftershocks
	Immediate damage to non-structural components and services (repair or replace)	Delayed damage to non-structural components and services (repair or replace) because the structure was not repaired in time for aftershocks
	Immediate damage to content and equipment (repair or replace)	Delayed damage to content and equipment (repair or replace) because it was not evacuated and the structure was not repaired in time for aftershocks
Human	Immediate fatalities	Delayed fatalities due to uninterrupted use of damaged structure which later collapses
	Immediate injuries	Delayed injuries due to uninterrupted use of damaged structure which later collapses
	Immediate trauma	Delayed trauma due to uninterrupted use of damaged structure which later collapses
Function	Loss of residence due to immediate damage	Loss of residence due to delayed damage in aftershocks
	Business interruption due to immediate damage	Business interruption due to delayed damage in aftershocks

For all categories of consequences or costs, i=1, …, N, it is necessary to establish a relationship between a parameter quantifying the extent of damage, x, and the associated cost $C_i(x)$. The corresponding expected cost or risk R_i can then be calculated as

$$R_i = \int C_i(x) f_{DS}(x) dx \qquad (13)$$

where $f_{DS}(x)$ is the probability density function for damage extent. Alternatively, the uncertainties in the relationship between the cost and damage extent can be taken into account and risk calculated as

$$R_i = \iint f_{(DS,C),i}(x,y) dxdy \qquad (14)$$

with $f_{(DS,C),i}(x,y)$ being the joint probability density function for category i of damage and costs.

6.1. Consequences to structure, non-structural components and content

The cost of structural damage resulting in the need to repair or replace structural components can be estimated from initial construction costs. A useful methodology is that adopted by HAZUS (FEMA 2003). It envisages four damage states: slight, moderate, extensive and complete. For a given occupancy and damage state of the building, the repair and replacement costs are calculated as the product of the floor area with the given occupancy, the probability of the building in the given damage state, and repair costs of the building type per unit floor area for the given damage state.

For non-structural damage, it is useful to distinguish between acceleration-sensitive components (ceilings, equipment that is an integral part of the facility such as mechanical and electrical equipment, piping and elevators) and displacement-sensitive components (partitions, exterior walls, ornamentation, cladding and glass) (Kanda and Shah 1997, FEMA 2003).
Building contents include furniture, equipment that is not integral with the structure, computers and similar, and business inventory. It is assumed that most contents damage, e.g. fallen cabinets and equipment falling off tables will be caused by excessive accelerations. It is also assumed that even in the complete damage state 50% of contents can be retrieved.

FEMA provides tables and formulas from which estimates of the costs of the aforementioned damage categories can be obtained.

6.2. Consequences to humans

6.2.1. Fatalities

Fatalities due to seismic damage to buildings can be divided into those resulting from structural collapse, no-structural causes and follow on effects, such as fires (Coburn et al. 1992). For low levels of damage, the non-structural fatalities usually dominate but are variable and hard to predict, while for stronger damage the fatalities from structural collapse are most important. The follow on effect fatalities occur rarely, but if they do they can be dominant.

Coburn et al. (1992) proposed a model for predicting the numbers of fatalities from collapse based on an analysis of data from 1,100 earthquakes that occurred worldwide. Their model appears to be formulated for average fatalities in a large stock of structures, but can nevertheless be adapted for the single building for which monitoring is being considered in the following way:

$$N_f = M_1 \times M_2 \times M_3 \times \left(M_4 + M_5\right) \tag{15}$$

where N_f is the expected number of fatalities, M_1 is the maximum number of people in the building, M_2 is the occupancy ratio at the time of earthquake, M_3 is the ratio of occupants trapped in the building, and M_4 and M_5 are the ratio of those trapped killed immediately in collapse and those who will die later as the result of not being rescued on time.

It can be assumed that the maximum number of occupants (and clients or guests), M_1, will be approximately known for the building concerned, perhaps as a result of a specially designed survey or using a system that monitors the number of people coming in and out of the building. The cost of such surveys or monitoring and data analysis may need to be included in the decision making process. Otherwise the numbers can be estimated from average occupancy data. For example, British Council of Offices (2013) gives an average figure of one workplace per 10.9 m^2 of net internal area and provides breakdowns per different sectors. It should be emphasised that building population numbers may change quickly, for example as a result of an economic downturn.

The occupancy ratio at the time of earthquake, M_2, will depend on the type of building. Offices and commercial buildings will normally be at their peak occupancy during business hours, whereas residential buildings outwith those hours. Weekly, or even monthly or annual, occupancy cycles may also need to be considered if appropriate. It is again envisaged that more accurate data will be available for the building, but average occupancy figures can be used instead if necessary (Nathwani 1997).

There is evidence from previous earthquakes that, luckily, many occupant manage to escape before the building collapses fully or partially or manage to free themselves quickly. This will depend on the time it takes for the structure to collapse, e.g. brittle and weak structure may collapse nearly immediately, whereas ductile structure may offer a window of time for people to escape. Where occupants are at the time of earthquake is also a critical factor and if evacuation routes and exits are easily accessible, with those occupants being in the ground floor having the largest chance of leaving the building on time. Janssens et al. (2011) proposed to link calculating the M_3 ratio to the relative area of the floors that collapse. Following this concept, the following formula is proposed herein:

$$M_3 = \frac{1}{M_1}\sum_{i=0}^{n}\gamma_i N_i\left(A_{col\%,i}\cup A_{col\%,i+1}\right) \tag{16}$$

where index $i=0, 1,\ldots, n$ refers to floors (i=0 corresponds to the ground floor and i=n to the roof), M_1 is, as previously, the total number of people in the building , N_i are the number of people on each floor, and γ_i is the number of people from each floor that are expected not to escape. This last number may be small when collapse affects most of the structure: Coburn et al. (1992) suggested that only 50% of the occupant of the ground floor will be able to evacuate themselves in time in such cases. The formula assumes that people will be trapped by either the collapse of the floor they are on, i, or the one immediately above, i+1, and $A_{col\%,i}\cup A_{col\%,i+1}$ is the area of the union of the vertical projections of collapsed areas of these floors in per-cents.

For factors M_4 and M_5, there are some estimates available in Coburn et al. (1992) suggesting, e.g. 0.4 for M_4 and 0.7-0.9 of the difference between M_3 and M_4 for M_5 for reinforced concrete buildings.

To fully quantify the consequences of fatalities in monetary terms it is necessary to assign economic value to human life. Several approaches are listed in Janssens et al. (2011). The approaches based on the so-called willingness to pay or willingness to accept are taken from historical records of compensation following collapses. Faber et al. (2004) report that average compensation per fatality was 2.08 million USD for the victims of the 2001 World Trade Canter collapse. The value of statistical life is the value that an individual assigns to a change in the probability of avoiding their death. This data is often taken from studies that look into how much compensation workers are willing to accept while undertaking a more risky job or the willingness to pay for improvements to safety. In that context, the UK Health and Safety Executive (2001) uses 1 million GBP as the value of preventing loss of a single life. The life quality index approach (Faber and Stewart 2003) takes into account life expectancy and gross domestic product per capita, calibrating the model such that a value between 2 and 3 million USD results.

6.2.2. Injuries

Spence (2007) discusses the modelling the extent of injuries sustained in earthquakes. The report acknowledges there are noticeable uncertainties, inconsistencies and general sparsity of available data on which to base predictive models. Unlike deaths, which result mostly from building collapse, injuries are often sustained even if the building structure is less severely damaged, can results to a larger extent from non-structural damage, and can affect individuals that were not necessarily trapped in the building. The report proposes using five levels of injury severity ranging from uninjured/lightly injured through to critical injury (and death as level five but this last level has already been covered in Section 6.2.1). These levels of injury are proposed to be linked to five levels of building damage on the European Macroseismic Scale (Coburn and Spence 1992) via percentage distribution of each injury levels corresponding to each damage state, and sample numbers are given for different construction types of heights for the highest damage stage.

Once the numbers of injured people and their injury extents are assessed, the costs of injuries can be estimated. A useful tool for doing so may be guidelines on amount of compensation to which an injured person may be entitled, such as PIAB (2004).

6.2.3. Trauma

Post-earthquake trauma may take form of fear, feeling of helplessness, distress, and depression even leading to potential suicides (Faizian et al. 2005). These consequences may lead to direct costs related to their treatment and loss of efficiency amongst affected workers and can continue even long time after the earthquake occurrence.

6.3. Consequences of loss if building function

The consequences to building function include loss of rent by the owners and interruption to business and loss of business inventory due to various types of damages. The cost of using an alternative location for business operations or for living for the time inspections and repairs are undertaken should also be included. The duration of business interruption will generally be shorter than duration of repairs because businesses will hire alternative space for the duration of repair. The time required to repair a damaged building will comprise the time for preparations such as obtaining funding, permits and preparing design, and then construction and clean-up time. For more severely damaged structures, the preparatory tasks may considerably increase the actual repair time. FEMA (2003) provide formulas and parameters for estimating the costs related to the various aspects of building function loss.

7. Conclusions

This factsheet proposes a decision making framework for rationalising adoption of monitoring systems for buildings exposed to seismic risk. The benefits of monitoring are quantified in terms of the reduction of the risks posed by the failure of structure to be monitored versus the cost of a monitoring system. The decision making framework is formulated as a pre-posterior decision problem. Two types of monitoring are proposed for either quick post-event appraisal of a single building state and damage or for updating the seismic risk to structures through long term monitoring. For the quick post-event condition assessment, it is proposed how methods for automatic damage detection and joint utilisation of monitoring and visual inspection data can be used in the pre-posterior analysis. Modelling of the various consequences or costs of earthquakes, including damage to structural and non-structural components and content, human fatalities, injuries and trauma, and loss of building function are also discussed to be able to model risk fully.

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