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ORIGINAL RESEARCH PAPER

On-site structure-specific real-time risk assessment: perspectives from the REAKT project

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Abstract The availability of computationally powerful and energy-efficient wireless sensing units or WSUs (one or more arranged in the form of a network in the vicinity and/or within a structure of interest) has led to new developments in the field of building and seismic strong motion monitoring. These WSUs can serve several functions. Those of largest earthquake engineering and engineering seismology interest are the recording of ground shaking the building is subjected to, as well as its response, and the capability of running rapid seismic risk analyses on the basis of vulnerability models of the structure, possibly coupled with recorded data. The REAKT project has shed light on a number of prospective applications of the last generation of monitoring devices for seismic risk management of critical structures. These applications refer to real-time and near-real-time risk assessment, that is: earthquake early warning, immediate post-event response evaluations based on recorded shaking, and short-term aftershock risk management for automated building tagging. This paper summarizes these perspectives that, despite still presenting some challenges that may limit readiness to date, have potential for scientific innovation in the field.

Keywords Building monitoring · Performance based earthquake early warning · Wireless sensing units · Seismic risk assessment

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1 Introduction

The measurement of vibration of ground and of structures, as a response to natural or forced excitation, has played a fundamental role in the development of engineering seismology and earthquake engineering (Cloud 1964; Housner 1983; Hudson 1992; Reitherman 2012). In the 1930s, the interest of seismologists and engineers in recording strong shaking led to the development of the first accelerograph (Wenner 1930, 1932) and, in turn, to the recording of the first strong motion data, relevant to the Mw 6.4, 1933 Long Beach earthquake (Hauksson and Gross 1991). As pointed out by Cloud and Carder (1956), ongoing development in sensor technology always has played a critical role in improving the performance of building monitoring systems. An example is provided by the wireless sensing units (WSU) with embedded computing capabilities introduced in the late 1990s (Straser and Kiremidjian 1998; Lynch et al. 2001). The possibility to install software on the WSU for real-time data processing and communication, made these sensing units suitable for *structural health monitoring* (SHM), considering also their low cost of production and deployment (e.g., Lynch et al. 2004; Lynch and Loh 2006).

Object of this study is to discuss some perspective for *real-time* (i.e., during an earthquake) and *near-real-time* (i.e., right after a potentially damaging event and/or during its aftershock sequence) structure-specific risk assessment, aided by data acquired from one or more (i.e., a network) of such wireless sensing units (WSU), installed in the vicinity or within a building or, more generally, a structure of interest. The discussed vision reflects the results of several projects, the last of which is the REAKT European project (*Strategies and Tools for Real Time Earthquake Risk Reduction*; see acknowledgements), aimed at seismic risk assessment of structures at various time-scales. For the sake of clarity, in the following we will refer to the *acquisition layer* of the sensing units when discussing the real-time acquisition and communication, and to the *processing layer* when applying algorithms for processing the data coming from the acquisition layer, integrating the computation with information about the building characteristics stored in the units.

The sensing units may be devoted to collect both ground and structural vibration data. One of the key features of the WSUs is their possibility to perform decentralized (i.e., local to the WSU) actions. In the framework of SHM these actions are typically devoted to provide information useful to infer the structural conditions or their evolution in time (e.g., Lynch et al. 2003; Hsu et al. 2011). However, the computation capabilities of the units allow to expand the range of possible applications at different time-scales of seismic risk, including, for example, the seismological earthquake early warning (EEW) (e.g., Wu and Kanamori 2005; Satriano et al. 2011).

Regional seismic monitoring networks (i.e., sensors of ground motion deployed in wide geographical areas) have been already coupled with the real-time risk of structures assessment through the so-called performance-based earthquake early warning (PBEEW) approach (Iervolino 2011). In PBEEW, the probability distribution functions of the earthquake's location and magnitude, provided by a regional seismic network, are used as input for structure-specific seismic loss assessment which, in turn, supports the decision whether to issue a warning before the ground motion reaches the target. The computational power of the WSUs may allow to extend the PBEEW using data on-site with respect to the building as opposite to use those from regional networks. As discussed in the following, the interaction in the processing layer of the on-site seismological EEW and PBEEW modules makes virtually possible (some issues still exist) the definition of warning protocols based on probabilistic damage prediction (e.g., Iervolino et al. 2014b; Bindi et al. 2015b), as some prototypal applications show.

At a different time-scale, that is the one of weeks/months after a possibly damaging earthquake, it seems particularly appealing the possibility to use the WSU to provide the necessary data to the models which inform the probabilistic predictions of aftershock structural risk. Indeed, this could allow the short-term evaluation of the failure probability during an aftershock sequence, which can be useful to rationally regulate the occupancy and eventually to reduce the downtime of the structure and the business it serves.

In the following sections, we first provide a brief historical overview about the development of the building monitoring (which herein means simply to have one or more WSUs close to, or within the building). Then, we introduce three different risk assessment frameworks (i.e., different goals and possibly time-scales) where the monitoring with WSU was applied within REAKT, that is: (i) SHM, in the long term or after an earthquake: (ii) real-time during an earthquake, that is seismological EEW and PBEEW; and (iii) during aftershock sequences to potentially damaging earthquakes, that is near-real-time short-term risk assessment. Finally, prototypal applications are briefly presented along with a discussion of critical issues still open for future developments.

2 Historical overview

Strong motion seismometry started in the early 1930s with the installation in California of the first strong motion station and the recording of the 1933, Long Beach earthquake (Freeman 1932; Wenner 1932; Cloud 1964; Housner 1983; Trifunac 2009). The roots of strong motion seismometry extend to the beginning of the instrumental era, and in particular during the second half of the nineteenth century when in Italy (Cecchi), Japan (the British scientists Ewing, Milne and Gray) and Germany (Wiechert), the first seismographs were constructed (Dewey and Byerly 1969; Ben-Menahem 1995; Trifunac 2009).

While the interests of seismologists in the early years were mainly devoted to recording distant earthquakes to investigate the properties and structure of the Earth's interior, engineers moved their attention towards the impact of earthquakes on structures (Freeman 1930; Heck 1930) and on the response of soil to ground shaking (e.g., Rogers 1930; Jacobsen 1930). Early observations on building damages caused by an earthquake were performed in Europe by Mallet (1862) while in Japan, between late nineteenth and early twentieth centuries, Milne and Omori developed a pioneering program for measuring damages, mainly in masonry constructions, using a shake-table (Davison 1924; Hudson 1992; Reitherman 2012). In California, an impulse to the development of seismic engineering studies was provided by the 1906 San Francisco and the 1925 Santa Barbara earthquakes (Binder 1952; Maher 1964; Reitherman 2006). After the 1929 World Engineering Congress held in Tokyo, and following the monitoring experiments performed in Japan (Suyehiro 1931), an intense program for measuring vibrations inside buildings was established in California (e.g., Cloud 1964). Examples are the empirical assessment of the natural periods of several tall steel frame buildings with reinforced concrete floors and walls (Byerly et al. 1931), and the measurements performed under the California Seismological Program of the United States Coast and Geodetic Survey at Stanford University (e.g., Carder 1936, 1937). The activities associated with the empirical evaluation of a building's response to ambient vibrations were accompanied by attempts of using forced vibrations (Rogers 1930; Blume 1935) and experiments with shake tables (e.g., Ruge

1936). Regarding theoretical developments, in the same years, several authors studied the elastic response of simple systems like a rod with a clamped end, excited with a transient signal or harmonic motion. These models were used to provide the first interpretations to the empirical results. Examples include the work of LeConte and Younger (1932) about the bending moments and distribution of stress in a vertical elastic rod when the base is subjected to a simple harmonic motion. Biot (1933) developed a theory for describing the response of elastic systems vibrating under transient impulse, introducing the concept of response spectrum (Riddell 2008), and Housner (1941) calculated the response of an oscillator to a generic input.

Starting from the 1930s in California and after World War II in Japan, programs for developing strong motion networks to monitor both the structural response to earthquakes and the variability of the input motion due to site effects were established (Cloud and Carder 1956; Takahasi 1956; Trifunac 2009). In particular, Cloud and Carder (1956) provided a summary about the project undertaken by the Program of the Coast and Geodetic Survey, where the importance of developing instruments cheap enough to allow dense installations both in terms of spatial coverage of the selected buildings and as networks inside each building was highlighted. The rapid technological developments occurred during the last decades of the twentieth century allowed the realization of low cost sensing units with embedded computational power and exploiting the wireless communication. WSUs show several advantages: the computing power allows the units to run local analyses and to optimize the power consumption related, for example, to the communication. They are easy to install since the wireless link does not require the deployment of cables for the data transmission and cheap, allowing dense installation inside a building at reasonable cost (Lynch and Loh 2006).

Since the development of the first WSU (Straser and Kiremidjian 1998; Lynch et al. 2001; Wang et al. 2007), many prototypes have been put forward both in the academia and industry. As an example, the Self-Organizing Seismic Early Warning Information Network (SOSEWIN) WSU was realized within the framework of the EU-FP6 SAFER (Seismic Early Warning for Europe) and German EDIM (Earthquake Disaster Information system for Marmara region, Turkey; http://www.cedim.de/EDIM.php) projects for earthquake early warning purposes (Fleming et al. 2009, Picozzi et al. 2011, Fischer et al. 2012). REAKT allowed considering and further developing the strategies to deploy SOSEWIN networks in different buildings (Parolai et al. 2014; Esposito and Emolo 2014; Karapetrou et al. 2014). The SOSEWIN units define a decentralized, self-organizing ad-hoc wireless mesh network (WMN) where each sensor undertakes its own, on-site data processing, preliminary analysis, archiving, and communication of data, as well as the issuing of early warning messages. In the following, we introduce some modules for risk assessment that can be installed in the processing layer of the WSUs, which will be considered as the reference for the other applications described herein.

3 Modules for the WSU processing layer

As discussed above, the technological advances of the last three decades allowed the development of modular sensing units suitable for performing building monitoring. The modularity approach permits to adapt the WSU to the specific monitoring needs, selecting the most suitable sensors for any specific task. Herein, we mainly consider WSU designed to record strong motion data with microelectromechanical systems (MEMS) accelerometers. The capability of the sensing units to process in real-time the acquired data makes the sensing units suitable for a wide range of applications as discussed in the following. Original developments of the authors and those within the REAKT project, can be identified by the references cited and the applications, respectively.

3.1 Structural health monitoring

The term SHM generally indicates an ensemble of sensing technologies and analytical methods that can be used to rapidly identify the occurrence of damage in monitored structures (e.g., Lynch and Loh 2006; Brownjohn 2007). In the context of SHM, damage can be defined as a change introduced into a system that adversely affects its current or future performance (e.g., Farrar and Worden 2007). The process of damage detection includes the identification of changes in the structure response to some kind of excitation (e.g., seismic) which could be proxy for the damage occurrence, the identification is generally performed by comparing the actual state with a reference one, generally representing the undamaged state. Moreover, the damage detection process develops through a multi-layer approach including a sequence of actions at increasing levels of complexity, such as existence, location, type, extent, prognosis (Rytter 1993). Depending on the application, the damage detection algorithms can be classified as local-based or global-based (e.g., Lynch and Loh 2006). While in the local-based method the screening of damage is performed at the length-scales of a component or sub-component of a structure, the global-based methods consider the structure as a whole, monitoring vibration characteristics like mode shapes, velocity of wave propagation, etc. Many potential damage detection algorithms have been proposed in the literature (e.g., Doebling et al. 1996). Starting from the first prototype of sensing unit with wireless communication (WiMMS, Straser and Kiremidjian 1998), that implemented an algorithm based on measuring the *Arias intensity* as a damage indicator, different classes of damage algorithms have been embedded in the WSUs (Lynch and Loh 2006). Examples are methods based on monitoring changes in the frequency response of the system (e.g., Lynch et al. 2003; Hsu et al. 2011); those based on modal analysis (e.g., Zimmermann et al. 2008); and pattern recognition approaches (e.g., Sohn et al. 2001), such as time-series analysis based on auto-regressive with exogenous inputs (Sohn and Farrar 2001).

Recently, approaches based on monitoring the characteristics of the wave propagation within the structure have been considered for implementing damage detection algorithms. Since Kanai (1965), the building response has also been estimated following waveform approaches based on the properties of seismic waves propagating inside the building. In the context of the waveform approaches, the interferometric approach (Aki 1957; Clearbout 1968; Snieder and Safak 2006) has been widely used to evaluate the shear wave velocity and attenuation inside a building using earthquake data recorded at different floors (e.g., Snieder and Safak 2006; Kohler et al. 2007; Picozzi et al. 2011; Nakata et al. 2013; Rahmani and Todorovska 2013). In particular, interferometry has been used to detect changes in the travel times of seismic wave propagation through the structure (Fig. 1).

By assuming the vertical distribution of mass to be known, the velocity changes can be in turn related to a loss of stiffness due to damage. When the sensors are installed at different floors, the change of the travel time between pairs of sensors after an earthquake can be exploited to determine the occurrence of damage and to localize it. An early application of such an approach was given by Todorovska and Trifunac (2008), who analyzed the recordings of the 1979 Imperial Valley earthquake inside the Imperial County

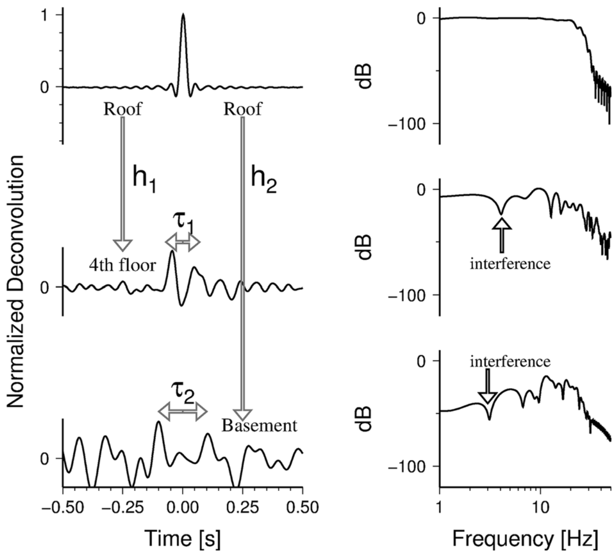


Fig. 1 Example of seismic interferometry applied to the AHEPA hospital in Thessaloniki, Greece. *Left*: the deconvolution between ambient noise recordings (stacked over 1 h) at different floors considering the roof as the reference station; the time lag (τ) between the up-going (time < 0) and down-going (time > 0) pulses and the distance (h) between the considered floor and the roof are used to estimate the average shear-wave velocity between the sensors. *Right*: amplitude Fourier spectra of the interferograms shown in the left panels; the negative interference between the up- and down-going waves generate the troughs in the spectra (for details, see Bindi et al. 2015a)

Service building. By applying interferometry to three time windows selected before, during and after the strongest shaking phase, the authors showed that the spatial distribution of the velocity before the earthquake was in agreement with spatial distribution of the stiffness as expected from the building design. Then, they showed that the distribution of velocity changes before and after the strong motion phase was consistent with the damage pattern observed after the earthquake.

Within the framework of the REAKT project, the AHEPA hospital in Thessaloniki (Greece) was instrumented with 13 WSUs, equipped with three-axial accelerometers and installed at different floors for real-time monitoring (Bindi et al. 2015a; Karapetrou et al. 2016). Since the units were connected to the electric power line and also equipped with a 17A back-up battery, the issue of the power consumption was not investigated during this experiment. The real-time streams were continuously transferred through the WSU network and towards the data center. Considering the computing power of the units, a deconvolution algorithm could be embedded in each WSU and the interferometry computed between units installed at different floors. Figure 2 exemplifies the application of the interferometry to AHEPA, by showing the deconvolution results obtained for three windows selected before, during and after an earthquake of magnitude 3 occurred at a distance of 15 km from the hospital. Considering the small magnitude of the event, changes in response were not expected, as confirmed by the constant time lag (within one time sample) between the up- and down-going pulses computed over the three time windows.

The possibility to store in the sensing unit a (simplified) structural model of the building (e.g., in terms of modal decomposition and impulse response) allows the prediction of the

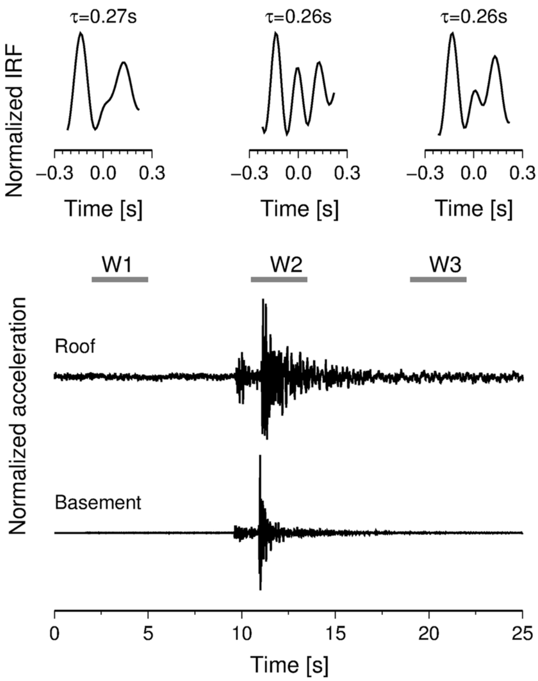


Fig. 2 Deconvolution for three windows (indicated by the *gray horizontal bars* W1, W2, and W3) selected before, during and after an earthquake recorded at the basement and roof of the AHEPA hospital. The normalized deconvolution (IRF, impulse response function) for the three windows is shown in the top frames, were the time lag (τ) between the up- and down-going pulses is also provided. The traces are sampled at 0.01 s

level of shaking at different floors using data from a single seismometer (Kohler et al. 2013). For example, Cheng et al. (2015) considered the shear beam model to predict the wave propagation in a 54-story building in Los Angeles (California) excited by the Mw 5.4 Chino Hills earthquake while Cheng and Heaton (2015) applied the Timoshenko beam model to study the response of the Millikan library.

The modal shapes of the AHEPA hospital in Thessaloniki were derived from dense noise measurements and applying standard operational modal analysis techniques (Bindi et al. 2015a). The modal decomposition of the building could be uploaded in the WSU and used to estimate in real-time the building motion at a given floor using the recording available at another floor. In fact, Parolai et al. (2015) showed that for simple structures the shaking at the top floor can be simulated by implementing a recursive calculation of the acceleration and/or of the displacement that a single degree of freedom oscillator would experience at the same instant. They also showed that the approach might also work for more complicated structures by accounting for the contribution of different modal frequencies (like in the AHEPA hospital case). The mainboard of the WSU installed in AHEPA was equipped with an AMD Geode LX800 CPU at 500 MHz and with 256 MB RAM (Picozzi et al. 2010). Because of the low computational demand required by the recursive procedures, the predicted shaking can be calculated in real-time for several different structures existing in an area and characterized by different a priori known structural models, with just a few WSUs instrumenting one building only in the area. For example, with WSUs close to or within one building only, and assuming that the ground motion is the same for neighboring structures, if the WSUs contain simplified models of the other buildings, their response can be rapidly inferred. The check of the values predicted for the relative displacement of the structure provides then first-order information about the level of drift that the buildings might have suffered due to the earthquake shaking.[1]

Figure 3 shows the example of the motion predicted at the roof of the AHEPA hospital using the motion recorded at the first floor. In the left panel the results are shown considering as input ground motion the shaking generated by a Ml 6.2 regional event occurred at a distance of about 200 km. In the right panel the results are shown considering as input an event of local magnitude Ml 5.2 that occurred at a distance of about 90 km. It is worth noting that while the low-frequency rich signal of the regional event is able to excite the fundamental mode of the structure, explaining a large part of the vibration observed at the top (blue seismogram), the local event signals mainly excites the higher modes of the structure. The average ratio η, computed as the sample-by-sample ratio between recorded and simulated accelerograms averaged over the signal duration, decreases from $\eta = 0.75$ to 0.41 for the cases of magnitude 6.2 and 5.2, respectively. This confirms the better reproduction of the actual shaking for an event stronger enough to trigger the fundamental mode. In both cases, however, a simple real-time recursive calculation is able to fairly accurately reproduce the shaking observed at the top of the structure.

3.2 Seismological earthquake early warning

The capability of the WSU to process the acquired data in real-time can also be exploited for seismological earthquake early warning. Two main typologies of seismological EEW systems are generally implemented (e.g., Satriano et al. 2011), namely the regional (or network based) and the on-site (or single-station-based). In the regional approach, a network of stations is installed close to the source area in a way to detect the occurrence of an earthquake early enough to characterized its location and magnitude before the destructive S-waves reach the target site protected by the EEW. The time warning (or lead-time) is defined as the difference between the arrival time of the S-wave at the target and the time at which the alarm is issued. Since the regional EEW is implemented to protect the target with respect to a specific source zone, the lead-time is almost constrained by the characteristics of the network depending on the P-wave arrival times at the stations closest to the source (e.g., Behr et al. 2015). The decision about issuing an alert is based on the ground shaking expected at the target site, as computed through empirical ground motion models for the specific magnitude-distance scenario.

In the on-site EEW systems, the station is installed close to the target and the alert protocols are generally based on threshold values applied to the amplitude of the recorded ground shaking. By calibrating empirical models relating the maximum P-wave displacement over an early window from the trigger (e.g., 3 s) to the maximum velocity observed in the S-wave window (e.g., Wu and Kanamori 2005; Böse et al. 2009; Zollo et al. 2010), the threshold values can be applied to the early portion of the P-wave shaking. The lead-time for the on-site can be defined as the time difference between the S-wave and the P-wave arrivals at the target, reduced by the amount of time needed to evaluate the ground motion parameters over the P-waves (e.g., 3 s). The software for on-site EEW generally include modules for data pre-processing (in real-time using recursive filters), an event detection algorithm (generally based on short time over long time averages),

[1] In the case of non-linear structural response, ground motion recording at the site of the building may be used as an input to a non-linear model to gather information on the inelastic response (see the Sect. 3.3).

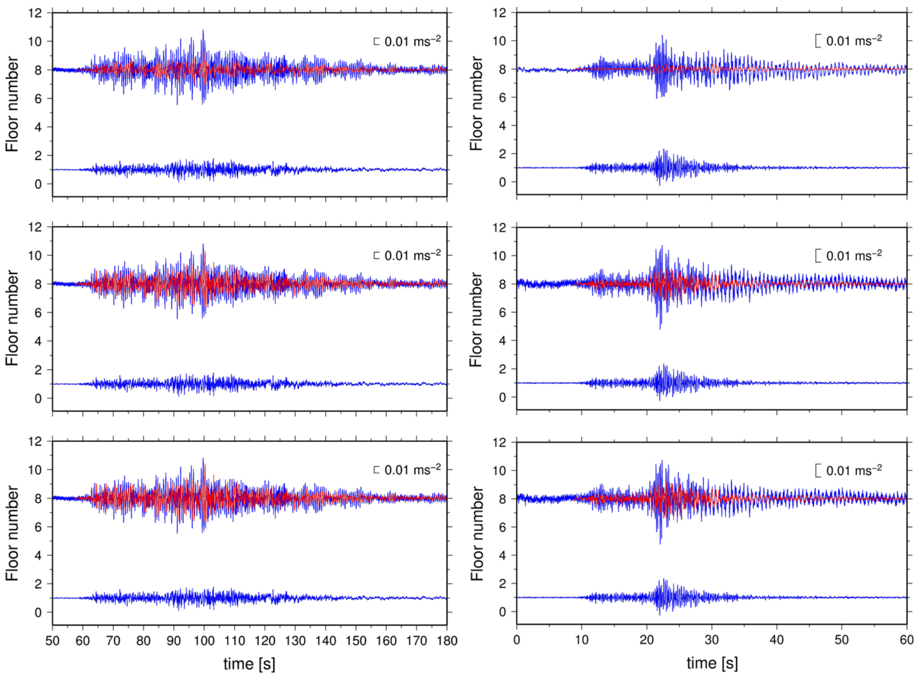


Fig. 3 The recording on the roof of the AHEPA hospital (*red line*) and its simulation (*blue line*) using the first mode frequency only (*top panels*). The lower traces (*blue lines*) are the recordings at the first floor used as inputs. The *bottom panels* show the same, but for the simulation carried out considering also the second (*middle panels*) and the third modes (*lower panels*), respectively. The *left panels* are the results obtained for the Ml 6.2 regional earthquake. The *right panels* show the results obtained for the Ml 5.2 local event

modules for estimation of the ground motion expected for the S-wave using ground motion parameters estimated for P-waves. An alert matrix can be defined by combining the expected ground shaking for S-waves in order to establish whether to alarm or not based on these seismological-based information; i.e., ground shaking predictions.

An example of application based on the measurement in the AHEPA hospital performed during the REAKT project is shown in Fig. 4. This Figure shows that the system was able to correctly identify the onset of both the regional and the local event recordings. The predicted peak ground velocity (PGV) on the horizontal components (see red and yellow lines in the bottom panels) overestimates the recorded PGV, likely due to the use of empirical predictions outside the range of magnitude and distance considered in their calibration. Even so, in both cases, no alarm level as defined in Parolai et al. (2015) was reached.

3.3 Performance-based earthquake early warning

In the processing layer of the WSU it can be also implemented modules for structure-specific real-time risk assessment, which is expected to be more informative than seismological EEW because it makes use of vulnerability and loss models specific for the structure served by the system. In fact, earthquake early warning is of engineering interest if the alarm can trigger security actions to reduce the seismic risk in real-time. The basic

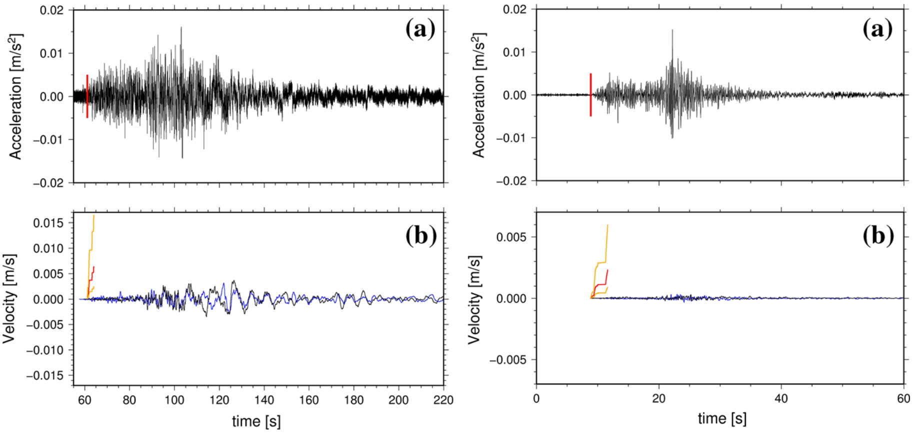


Fig. 4 *Top*: the acceleration recorded on the vertical component at the station in the first floor of the building for the Ml 6.2 regional (*left*) and the Ml 5 local event (*right*). The *red vertical bars* indicate the time of the triggering of the event. *Bottom*: the predicted PGV values (84 and 16 % confidence intervals in yellow and the mean in *red*) estimated from the vertical component and the EW (*blue*) and NS (*black*) velocity recordings of the Ml 6.2 regional (*left*) and the Ml 5 local (*right*) earthquakes. For details, see Parolai et al. (2015)

design variables for EEW applied to a specific building or facility system are: (i) the estimated earthquake features and related uncertainty; (ii) the available time before the earthquake strikes (lead-time); (iii) the performance (proxy for the loss) of the facility to protect, and related uncertainty, associated with the cases where the alarm is issued or not, which may also include the cost of false alarms and depends on the chosen security action. Seismological EEW refers to (i), while a framework to address also (ii) and (iii)—consistent with the principles of performance-based earthquake engineering or PBEE (Cornell and Krawinkler 2000) was developed in the SAFER project and named performance-based earthquake early warning (Iervolino 2011), and further addressed in REAKT (e.g., Cauzzi et al. 2016).

PBEEW assumes an existing regional seismic network, that is a wide system of instruments covering the area which is likely to be the source of earthquakes. Regional monitoring infrastructures are usually available in seismic regions and are operated by governmental agencies. This is why most of the ongoing research is devoted to exploiting these systems for EEW purposes. In fact, the work summarized in the following refers first to the feasibility and design of structure-specific EEW systems starting from the information made available in real-time from regional networks (i.e., during an earthquake, yet before the ground motion reaches the site served by the EEW system), which basically consists of the estimation of source features such as magnitude and the location of the earthquake.

In the framework of PBEE, the earthquake potential, with respect to the performance demand for a structure, can be evaluated via the so-called probabilistic seismic hazard analysis or PSHA (McGuire 2004). It consists of the probability that a ground motion intensity measure (IM), likely to be a proxy for the destructive power of the earthquake, is exceeded at the site of interest during the life-span of the structure. Because seismologists have developed several methods to estimate magnitude (M) and location (the latter readily provides the source-to-site distance, R) from the limited information carried by the

P-waves, the PSHA approach can be adapted for EEW purposes. This was called real-time PSHA or RTPSHA (Iervolino et al. 2006; Convertito et al. 2008), and is summarized by the integral in Eq. (1), which provides the probability density function (PDF) of the intensity at the site of the structure served by the EEW systems, $f_{IM}(im|\underline{\tau},\underline{s})$, conditional on the information provided in real-time from the seismic network.

$$f_{IM}(im|\underline{\tau},\underline{s}) = \int_m \int_r f_{IM}(im|m,r) \cdot f_M(m|\tau_1,\tau_2,\ldots,\tau_n) \cdot f_R(r|s_1,s_2,\ldots,s_n) \cdot dm \cdot dr \quad (1)$$

In the equation, $f_R(r|s_1,s_2,\ldots,s_n)$ is the PDF of the source-to-site distance function of (conditional to, in fact) a vector of data, $\underline{s} = \{s_1,s_2,\ldots,s_n\}$, from n stations of the network; $f_M(m|\tau_1,\tau_2,\ldots,\tau_n)$ is the PDF of the magnitude of the earthquake conditional to suitable information from the seismic sensors, $\underline{\tau} = \{\tau_1,\tau_2,\ldots,\tau_n\}$; and $f_{IM}(im|m,r)$ is the PDF of the ground motion intensity conditional on magnitude and distance[2]; e.g., from a ground motion prediction equation (GMPE).

From an engineering perspective, the real-time probabilistic assessment of a ground motion IM, although the first step from real-time seismology to structural performance, is neither the best option for evaluating the damage potential for a specific structure nor the more appropriate piece of information on the basis of which to decide whether to issue an alarm. In fact, it is known that the IM maybe only poorly informative with respect to the structural response. In other words, if one is able to quantify the loss specifically for the structure of interest, this is a sounder basis for the warning management.

The first step in this direction is extending RTPSHA to real-time probabilistic seismic response analysis (RTPSRA), which is the probabilistic assessment of the dynamic response of a structure to the impending earthquake detected by the seismic network informing the EEW system. The framing equation for RTPSRA is given by Eq. (2), where the $\mathrm{f}_{EDP}(\mathrm{edp}|\mathrm{im})$ term is the PDF of an engineering demand parameter (EDP), which serves as a proxy for the structural response, conditional to the earthquake intensity, to be obtained via structural analysis.

$$f_{EDP}(edp|\underline{\tau},\underline{s}) = \int_{im} \int_m \int_r f_{EDP}(edp|im) \cdot f_{IM}(im|m,r) \cdot f_M(m|\tau_1,\tau_2,\ldots,\tau_n) \cdot f_R(r|s_1,s_2,\ldots,s_n) \cdot dm \cdot dr \cdot d(im) \quad (2)$$

Based on RTPSRA it is not conceptually difficult to obtain the expected loss for the structure in the impending earthquake, $E[L|\underline{\tau},\underline{s}]$.[3] This is given in Eq. (3), where $f_L(l|edp)$ is the PDF of the loss conditional to structural response; i.e., the loss function.

[2] In fact, it has been shown that if at a given time t from the earthquake's origin, the seismic network can provide a vector of measures that are informative about the magnitude, then $f_M(m|\tau_1,\tau_2,\ldots,\tau_n)$ may be obtained in an analytical form via the Bayes' theorem. Likewise, because of rapid earthquake localization procedures, a probabilistic estimate of the epicenter may be available based on the sequence at which the stations trigger.

[3] The referenced studies consider the general case of vector-valued EDP and IM, as well the PDF of a damage measure given EDP (Eq. 3). It is easy to recognize that the representation given herein for the expected loss is equivalent. Note also that there are some conditional independency assumptions in the integrals of the equations; the interested reader is referred to the given references for details.

$$E[L|\underline{\tau},\underline{s}] = \int\limits_{l}\int\limits_{edp}\int\limits_{im}\int\limits_{m}\int\limits_{r} l \cdot f_L(l|edp) \cdot f_{EDP}(edp|im) \cdot f_{IM}(im|m,r) \\ \cdot f_M(m|\tau_1,\tau_2,\ldots,\tau_n) \cdot f_R(r|s_1,s_2,\ldots,s_n) \cdot dr \cdot dm \cdot d(im) \cdot d(edp) \cdot dl \tag{3}$$

The expected loss conditional on the information provided by the seismic network of the EEWS may be especially useful for a rational decision on whether to issue an alarm and undertake a safety action or not. Indeed, two expected losses can be computed via Eq. (3): the expected loss in the case of no warning $E^{\overline{W}}[L|\underline{\tau},\underline{s}]$, and the expected loss in the case of warning $E^{W}[L|\underline{\tau},\underline{s}]$. The two integrals used to compute these losses are identical except for the loss function term; for the former, $f_L^{\overline{W}}(l|edp)$ is used, which is the loss function if no alarm is issued (no security actions undertaken), while for the latter, $f_L^{W}(l|edp)$ is the loss reflecting the risk reduction (i.e., an alarm is issued and security measures taken).

In the cases where it is possible to compute, before the ground motion hits, the expected losses considering warning or not, one can clearly make the optimal (i.e., rational) decision, that is to alarm if and only if this reduces the expected loss, as presented in Eq. (4) (Iervolino et al. 2007).

$$To\ alarm \Leftrightarrow E^{W}[L|\underline{\tau},\underline{s}] \leq E^{\overline{W}}[L|\underline{\tau},\underline{s}] \tag{4}$$

As a simple example of PBEEW, the ERGO II system developed in the REAKT project is shown herein (Iervolino and Chioccarelli 2014). ERGO II is an EEW system performing RTPSRA for one of the main buildings of the University of Naples Federico II (Italy) and relies on real-time information from a regional seismic network deployed in one of the more seismically active areas in Italy. Indeed, in Irpinia, in the southern Apennines, a seismic network (ISNet) was installed in the first decade of 2000. ISNet is a local network of strong motion, short period and broadband seismic stations deployed in a 100 × 70 km^2 extent, covering the epicentral area of the main earthquakes of that region (including the Mw 6.9, 23th November 1980, event).

The seismic network is composed of about thirty stations with interstation distance of a few kilometers. The topology of the network was designed specifically to monitor, for earthquake early warning purposes, the entire Irpinia, extending across two Italian regions, Campania and Basilicata. ISNet is able to process and analyse in real-time the first P-wave signal from an occurring earthquake, providing in real-time progressively refined (i.e., as more stations will record the seismic signal) estimates of earthquake location and magnitude (Weber et al. 2007). Based on this information, ERGO II is able to provide, during an earthquake, the real-time estimation of the dynamic structural response of the considered building before the ground motion reaches it. The latter is a reinforced concrete moment resisting frame structure featuring thirteen storeys, two of which are underground. Numerical modelling of the structure (based on the information in Ranieri et al. 2010) allowed the retrieval of the PDFs $f_{EDP}(edp|im)$ for a few EDPs that are considered relevant structural response proxies. In particular, peak ground acceleration (PGA) was chosen as the IM, while peak floor acceleration (PFA), peak floor displacement (PFD) and the interstory drift ratio (ID), were selected as the EDPs. The distributions for these paramters (pre-computed and stored in a database to be accessed in real-time during an earthquake) are the characteristics of the structure relevant for PBEEW; see Eq. (2). In fact, when an earthquake occurs the ISNet feeds to ERGO II (installed in the building) the probabilistic estimates of magnitude and source-to-site distance for the earthquake developing in Irpinia, and ERGO II retrieves from the database the probabilistic evaluations of structural

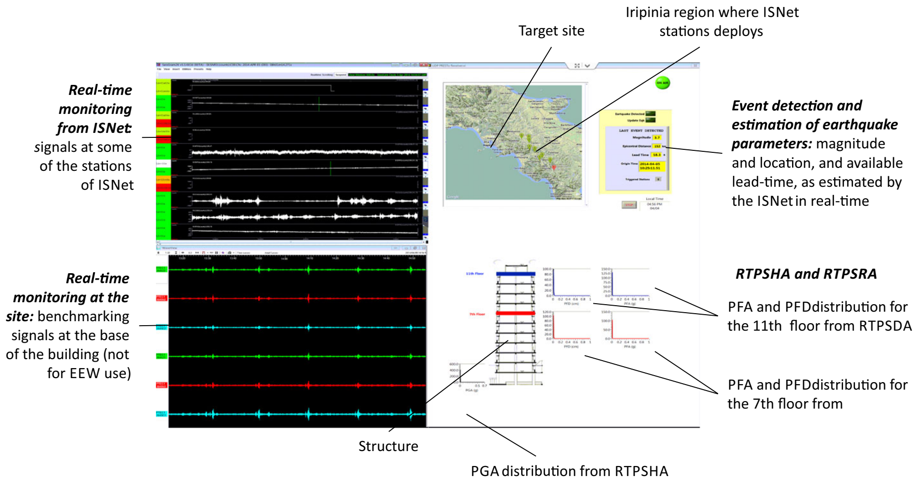


Fig. 5 Graphical interface of the ERGO II system

behavior suitable for the earthquake in progress, before the ground motion arrives at the building, with very low computational demand. This PBEEW system is currently operational and the graphical interface is now located in four different places of the protected buildings and it is sketched out in Fig. 5.

The interface, that so far has only demonstrative purposes and does not trigger any security actions, is divided into four panels:

1. *Real-time monitoring from ISNet:* in this panel the real-time accelerometric signals of the stations are shown on a ten minutes time window. Eight of the ISNet stations are represented and their locations are shown in panel two (in green). Triggering of a possible event is represented by a vertical line on the time-history.[4]
2. *Event detection and estimation of earthquake parameters:* This panel activates when an event is declared by ISNet. If this condition occurs, the magnitude and location are estimated in real-time as a function of the evolving information from the first panel. Moreover, on a map where also the stations are located, it shows the estimated epicenter, its geographical coordinates and the origin time.
3. *Real-time monitoring at the site:* similarly to the first one, this panel shows the real-time accelerometric signals recorded at the base of the structure by four stations located at increasing depth from 0 to −30 m. Although this information is not used by the EEW system, it can be useful for comparing probabilistic evaluations of the IM (PGA) with the actual recorded ground motions and to train the PBEEW system.
4. *RTPSHA and RTPSRA:* this panel performs both RTPSHA and RTPSRA for the site and the structure where the system is installed, based on information about magnitude and distance from panel two. In particular, it computes and shows the distribution of the expected PGA at the site of the structure [from RTPSHA of Eq. (1)] and of PFA and PFD of the 7th and 11th floor (arbitrarily chosen as an example) from Eq. (2).

[4] The system declares an event (M larger than 3) only if at least three stations trigger within the same 2 s time interval.

3.4 Issues in PBEEW based on local seismic sensors

In the previous section, we introduced some modules that can be implemented in the processing layer of the WSU. Aim of the present section is to discuss how these modules can be integrated in a single approach to risk assessment constructed upon the real-time acquisition layer. The discussion is presented in the form of an application of relevance for REAKT, namely the interaction between the on-site seismological EEW and the PBEEW modules.

The engineering applications of EEW discussed so far are based on regional seismic networks, since these are able to provide in real-time probabilistic estimates of magnitude and source-to-site distance, which are the basic elements of PBEE and then of PBEEW. On the other hand, because real-time data from regional networks, managed by geological surveys or other authorities, may not always be accessible, and also because of the development of continuous building monitoring, which is expected to make available seismic instruments at the structure's site, it may be interesting to develop structure-specific early warning systems based on hardware placed nearby or within the structure served by the EEW system. This is referred to as on-site EEW. However, in this case, the following issues arise, complicating the problem with respect to PBEEW:

(i) the estimate of magnitude is available for one location only that may imply intolerable uncertainty (see also Iervolino et al. 2009);
(ii) a reliable estimate of source-to-site distance may be difficult to obtain (although some attempts exist; e.g., Odaka et al. 2003), and may also carry large uncertainties;
(iii) the lead-time made available by on-site systems is only due to the different travel-times of P- and S-waves, whereas in the case of regional networks it may be larger because a significant portion of it is due to the fact that the earthquake features are estimated far from the target site, possibly even before the P-waves reach it.

Issues (i) and (ii) call for a change of paradigm in PBEEW. In fact, magnitude and distance are required by performance-based earthquake engineering only because they serve to estimate the ground motion intensity (in the case where the IM is sufficient in the sense of Luco and Cornell 2007). Therefore, if the local system can provide directly a probabilistic estimate of the intensity at the site based on the P-waves (PW), it is possible to estimate the earthquake consequences on the structure. If the onsite sensors can provide the distribution of the IM at the site, $f_{IM}(im|PW)$, and it is available for the structure of interest a fragility (or loss) curve, $P[DS|im]$, which expresses the probability of a damage state (DS) being exceeded as a function of IM (failure in this context is any damage or loss state of interest), then the EEW system based on on-site sensors can provide the probability that the structure is going to exceed DS by the arriving S-waves, $P[DS|PW]$; Eq. (5). This information can be used to start a security action if the risk (damage or loss probability) is unacceptable. Note that this is not dissimilar to Eq. (4).

$$P[DS|PW] = \int_{im} P[DS|im] \cdot f_{IM}(im|PW) \cdot d(im) \tag{5}$$

This paradigm simplifies if the on-site system is not able to provide the full distribution of intensity, but for example only its expected value, as shown in Eq. (6). In this case, the output of the EEW system is the value of failure probability from the fragility curve entered at the intensity value estimated by the on-site sensors.

$$P[DS|PW] \approx P[DS|E[IM|PW]] \tag{6}$$

Regarding issue (iii), it may be that for some close (and then potentially damaging) earthquakes a structure equipped with an on-site early warning system is in the blind zone of the earthquake (i.e., the region where the damaging shaking arrives before the alarm; Kanamori 2005), impairing effectiveness of the on-site EEW system.

Notwithstanding these a priori issues, it could be still worthwhile to investigate on-site PBEEW, to quantitatively assess limitations and potentials in the long run. Therefore, a prototypal application of the PBEEW coupled with WSUs was developed in the framework of REAKT in collaboration with the AXA-RF ISLAR project for monitoring an industrial facility in Italy (Iervolino et al. 2014b). Two WSUs were installed at the base and at the top of a column (Fig. 6, left). These WSUs have onboard the fragility functions of the building, which may be used as exemplified in Fig. 6 (right).

In fact, in this application, as soon as the WSU at the base triggers on the P-wave onset, the maximum vertical ground displacement is computed over a three seconds time window. This value is used to compute the expected value of the PGV for the S-waves on the horizontal components, for example using the semi-empirical models of Zollo et al. (2010). At this point the fragility curves for the buildings, which represent probabilities of exceeding damage states as a function of PGV, are entered with the expected value of PGV (Eq. 6) conditional on P-waves PGD or, even better, the PDF of PGV conditional on P-waves PGD (which Zollo et al. 2010, allows to retrieve) can be used in the context of Eq. (5). This allows to establishing whether to issue the alert for the building, before, for example, the arrival of the S-waves, based on probabilistic damage predictions.

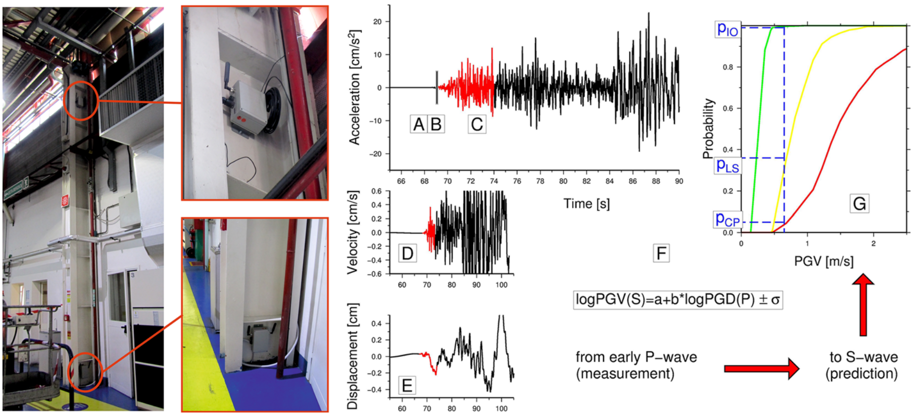


Fig. 6 *Left*: installation of instruments for on-site PBEEW and aftershock risk management in an industrial facility in Italy. *Right*: sketch of PBEEW application with on-site WSUs. *A* real-time strong-motion acquisition; *B* trigger based on short-time over long-time average; *C* estimation of strong motion parameters over 3 s after triggering; *D* estimation of parameters over velocity integrated signal; *E* estimation of parameters over displacement integrated signal; *F* prediction of PGV for S-waves using the peak ground displacement (PGD) over P-waves and using semi-empirical relations; *G* the fragility curves of the building are used to compute the probabilities of exceeding damage states P_{DS} [in the sketch, the immediate occupancy (IO, *green*), life safety (LS, *yellow*) and collapse prevention (CP, *red*) are shown]. Adapted from Iervolino et al. (2014b), and Bindi et al. (2015b)

3.5 Structure-specific aftershock risk management

Short-term risk assessment, that is at the time-scale of weeks/months around a major event, is gathering increasing research attention due to the compelling need for decision makers to have quantitative tools available that enable the management of such a risk. This is because major earthquakes (i.e., mainshocks) typically trigger a sequence of lower-magnitude events clustered in both time and space, which may be damaging for exposed assets. Therefore, risk management for structures in the post-event emergency phase has to deal with this short-term seismicity. Indeed, because the structural systems of interest might have suffered some damage during the mainshock, possibly worsened by damaging aftershocks, the failure risk may be large (e.g., unacceptable) until the intensity of the sequence reduces or the structure is repaired.

Recent advancements in probabilistic seismic hazard analysis allow to assess hazard of aftershocks following a major event of known magnitude and location. These efforts go under the name of aftershock probabilistic seismic hazard analysis (APSHA, Yeo and Cornell 2009). It was shown that, if a probabilistic model for the vulnerability of structures accumulating seismic damage is available, its combination with APSHA provides a time-variant seismic risk for the structure during the sequence (Yeo and Cornell 2005; Iervolino et al. 2014a). Note that this is a time-scale different from that of EEW, as it is employed after the mainshock to make probabilistic predictions with respect to the evolution of the aftershock sequence. Figure 7 sketches out the problem at hand, that is, during an aftershock sequence there may occur threatening events that could further damage an already affected structure, eventually leading to collapse.

In particular, the damage accumulation process is formulated in Eq. (7), where $\mu(t)$ is the residual structural capacity at time t, μ^* is the capacity at $t = 0$, immediately after the mainshock of interest, and $D(t)$ is the cumulated damage due to all aftershocks, $N(t)$, occurring within t. Both $\Delta\mu_i$ (damage in one aftershock) and $N(t)$ are random variables.

$$\mu(t) = \mu^* - D(t) = \mu^* - \sum_{i=1}^{N(t)} \Delta\mu_i \tag{7}$$

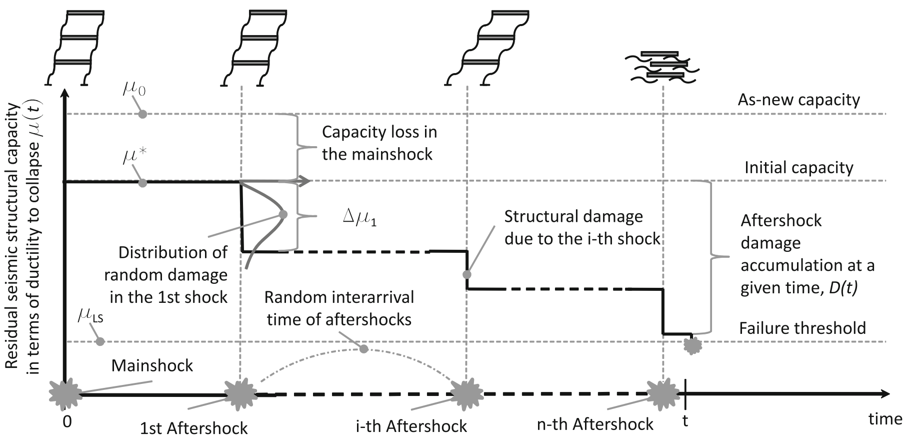


Fig. 7 Degradation process for a mainshock-damaged structure exposed to aftershocks, adapted from Iervolino et al. (2014a)

Given this formulation, the probability the structure fails within time t, $P_f(t)$, is the probability that the structure passes the limit-state threshold, μ_{LS}. In fact, it is the probability the cumulated damage is larger than the difference between the initial value and the threshold, $\bar{\mu} = \mu^* - \mu_{LS}$.

$$\begin{aligned} P_f(t) &= P[\mu(t) \le \mu_{LS}] = P[D(t) \ge \mu^* - \mu_{LS}] = P[D(t) \ge \bar{\mu}] \\ &= \sum_{k=1}^{+\infty} P[D(t) \ge \bar{\mu} | N(t) = k] \cdot P[N(t) = k] \end{aligned} \tag{8}$$

The last part of Eq. (8) makes use of the total probability theorem, to separate the randomness of the number of earthquakes that may occur within t, $P[N(t) = k]$, from APSHA, and the effect these may produce on the structure in terms of accumulated damage, $P[D(t) \ge \bar{\mu} | N(t) = k]$; see Iervolino et al. 2014a) for details.

It may be shown that, if only information about the amount of damage to the structure as a result of the mainshock is available, then it is expected that even if the aftershock sequence is fading with time, the risk that the structure will fail increases if the considered time window (since the mainshock) increases. This is because more aftershocks are expected during a larger post-main-event period of time, which may accumulate damage to the unrepaired structure. This is depicted in Fig. 8, where on the left there is an example of the daily rate of aftershocks for an ideal seismic sequence following an M 6.3 event, while on the right there is the corresponding failure probability as a function of time for a simple structure exposed to damage accumulation.

The structural capacity immediately after the mainshock, μ^*, is a difficult parameter to assess. Instruments local to the structure may be helpful in assessing this important information, input for this kind of aftershock risk assessment models. In fact, even simply a measure of the IM of the mainshock may help to infer the damage state of the structure right after the mainshock (i.e., the starting point in the aftershock sequence) with the aid of fragility curves for the undamaged structure. A refined possibility is to run a structural response simulation, using a numerical model of the structure, using as an input the recorded ground shaking at the site.

Moreover, as it was also shown in Iervolino et al. (2014a), the evaluation of the aftershock risk may take advantage of other information, which may be provided by on-site WSUs, available at a certain point in time, t, during the aftershock sequence:

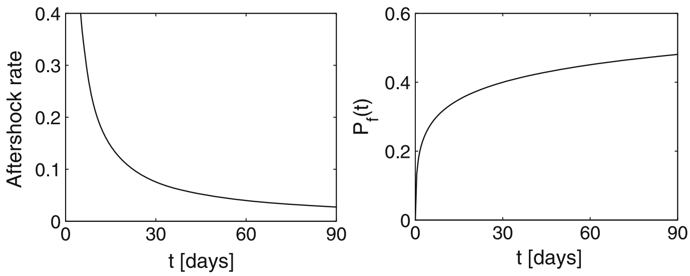
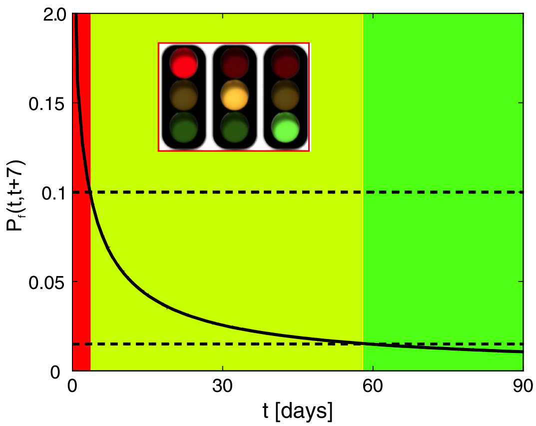


Fig. 8 *Left*: aftershock daily rate within ninety days following an Mw 6.3 mainshock (occurring at zero); *right*: failure probability for a simple structure with time following the mainshock (adapted from Iervolino et al. 2014a)

Fig. 9 Failure probability in the seven days following *t* given survival at *t* for a simple structure and tagging (adapted from Iervolino et al. 2014a)



1. the information that the structure at *t* has not yet collapsed;
2. a measure of the residual capacity of the structure at *t* (which may also be inferred by the ground motion intensities of the aftershocks the structure was subjected to up to *t*);
3. the number of damaging aftershocks the structure was subjected to up to *t*.

The availability of these data may substantially change the aftershock risk assessment. As an example, Fig. 9 shows for any value of *t*, and for the same structure and aftershock hazard of Fig. 8 (left), the probability of failure in the week after *t*, when it is known that at t the structure has not failed. It is apparent that the addition of this piece of information leads to a decreasing risk trend because, given that the structure is known to be standing at *t*, the hazard associated with the aftershock sequence is expected to decrease with time.

If one is able to probabilistically evaluate the time evolution of the failure probability, then one may be able to tag the building; i.e., to prohibit access to anyone (i.e., *red tag*), to allow access only to trained agents for emergency operations (i.e., *yellow tag*), or to halt business interruptions allowing normal occupancy (i.e., *green tag*); see also Yeo and Cornell (2005). To better clarify this concept, Fig. 9 also reports two (time-invariant) risks. The lower one is 1.5 %, the larger one is 10 %. Arbitrarily assuming 1.5 % as an intolerable collapse risk in one week during an aftershock sequence, and 10 % as an intolerable risk for emergency operations, it may be said that: before the failure risk intersects the largest probability (i.e., about the first five days after the mainshock), the structures is red tagged (i.e., cannot be accessed); it is green tagged after the aftershock risk gets smaller than the lower threshold (i.e., after about two months after the mainshock occurrence); between these two time boundaries, the structure is yellow tagged and can be entered only by trained operators.

Note that this aftershock risk management system may be installed on-board on WSUs and integrated in the same on-site PBEEW system discussed in the previous section; although this is a different risk assessment context. In fact, this was the case for the application Fig. 6 refers to, in which PBEEW and aftershock risk models for the structure are installed on the same sensing units.

4 Conclusions

This paper has presented a few perspective and prototypal applications of building monitoring in the framework of seismic early warning, structural health monitoring and short-term aftershock risk management, investigated and developed within the REAKT project.

The availability of WSUs with computing power allows to embed one or more of the approaches for seismic risk assessment in a single hardware infrastructure local to the building or the structure of interest. Moreover, the risk assessment models may take advantage of the data acquired by the WSU to better tailor and adapt continuously the models to the monitored structure. In fact, methods typical of EEW and SHM (e.g., trigger, P-to-S models, interferometry, etc.) define software modules that can be implemented in the firmware of the WSU. For example, the structural model of the building and a set of vulnerability/fragility or loss functions can be uploaded, allowing to combine the expected (early warning) or measured (near-real-time monitoring) shaking with the building performance.

We discussed seismological EEW and PBEEW modules such as: (i) module 1 involving embedded software for on-site early warning (trigger algorithm, application of empirical models to predict the ground motion from P- to S-waves); this considers a station installed in the free-field close to the building or in the basement; (ii) module 2 integrating module 1 by uploading to the sensing unit also a model of the building vulnerability (possibly including seismic damage accumulation) for EEW and/or aftershock risk management. For the SHM tasks, we discussed: (i) module 3, implementing software for estimating, in real-time, the building response at given floors using the recordings at the base; (ii) module 4, performing the interferometry in real-time.

Figure 10 provides a schematic where the different modules are combined. All these modules can be installed in the same WSU, allowing to assess the seismic risk over different time-scales, ranging from the probabilistic damage prediction in early warning to

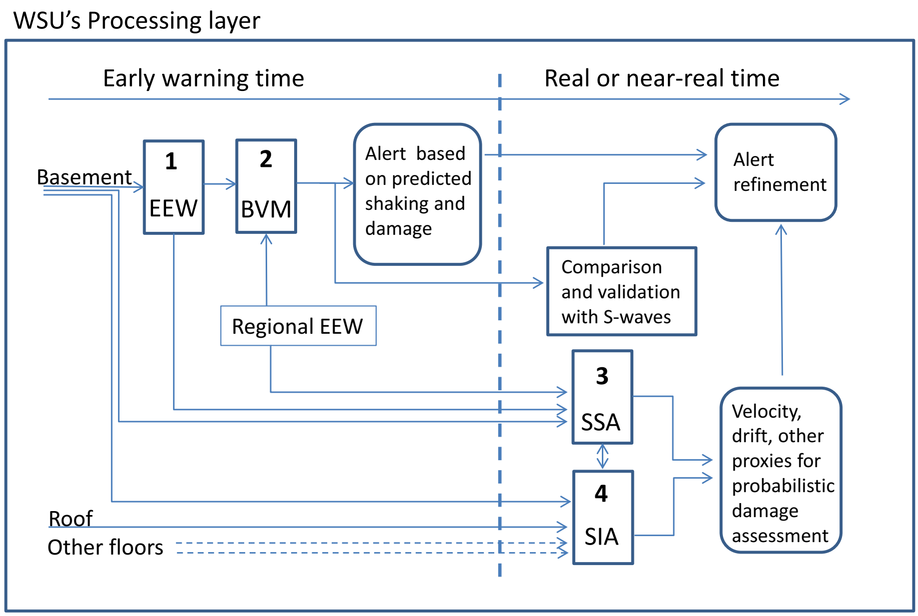


Fig. 10 Conceptual schema representing the interaction between different modules installed in the WSU. EEW: module for seismological on-site EEW; BVM: module for PBEEW using information from module 1 for performing probabilistic damage predictions; SSA: single sensor approach for estimating the building response at floors not monitored; SIA: seismic interferometry approach to monitor the velocity of the wave propagation in the building

the real-time applications for assessing the building response. We believe that the applications discussed herein, even if still posing significant challenges towards routine application, may encourage exploiting on-site instrumentation for seismic risk management of critical infrastructures.

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