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Use of Spectral Entropy for the damage detection in masonry buildings in presence of mild seismicity †

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Abstract: The seismic events that struck central Italy in 2016 caused severe damage to a wide range of buildings and infrastructures. Masonry buildings were particularly affected even for low values of peak ground acceleration. In this paper, the data recorded by three masonry buildings belonging to the Seismic Observatory of Structures (OSS) network are used to detect their seismic damage by means of Spectral Entropy (SE). However, entropy measures are sensitive to the energy inserted in the system, since an input of energy can bring to a more deterministic behavior of the structure and thus to a reduction of the entropy indicator. When non-stationary time series are used to evaluate the presence of damage (e.g. mild seismicity) the entropy of the system could be underestimated, leading to misleading results. For these reasons, in this paper an indicator based on the SE is proposed to assess the occurrence of damage also in presence of mild seismicity.

Keywords: structural health monitoring; spectral entropy; damage detection; masonry building

1. Introduction

The evaluation of the structural integrity of a building is one of the principal aim of permanent structural health monitoring (SHM) systems. The continuous monitoring of strategic buildings and structures has become a popular tool in the engineering practice, especially because it helps in their long-term maintenance and management, [1]. Within the SHM procedures, the ones related to the dynamic monitoring allows checking static and/or dynamic features of the monitored structure, by measuring the structural response on chosen strategic points. These procedures allow detecting the occurrence of structural anomalies which may indicate a damage. In the present paper, the Spectral Entropy (SE), [2], is used to detect the damage in three masonry buildings that were hit by the central Italy seismic sequence in 2016-2017. These buildings belong to the Seismic Observatory of Structures (OSS) network and their permanent monitoring systems recorded the various seismic events. The SE is employed to quantify the level of order/disorder of the time-series, where a non-stationary behavior of the signals is encountered. When damage occur, the level of SE increases due to the occurrence of irreversible system irregularities, which increase the disorder of the records. At the same time, the introduction of a deterministic behavior, such as the one related to the seismic input, decreases the disorder of the records leading to a lower estimation of the SE. The procedure proposed in the present paper allows the employment of the SE even for data recorded during mild seismic events, for which the seismic input would differ along the seismic sequence. Due to the seismic wandering related to the amplitude of the input, [3], the mild seismic records should be selected far from the main shock events, which can temporarily compromise the capability of damage indicators. The procedure brings to the definition of an entropy indicator, B_E, that is a parameter related to the SE-Energy (H-E) curve, where H and E are the SE and the energy of the signals, respectively.

2. Materials and Methods

The SE, [2], has been widely applied in mechanical engineering, [4], as well as in clinical and biological studies, [5], where there is the need to analyze pathological behaviors of complex phenomena (e.g. heartbeat). The SE use the Time-Frequency distribution (TFD) of a signal $x(t)$ to build a probabilistic distribution, $P(q)$, as follow:

$$P(q) = \frac{\sum_r S(r,q)}{\sum_q \sum_r S(r,q)} \tag{1}$$

Where $S(r,q)$ is the power spectrogram of the signal. By assuming an entropy measure, is then possible to evaluate the entropy over the probabilistic distribution calculated with Equation (1). In the present paper we assume the Shannon entropy measure in the information theory:

$$H = -\sum_q P(q) log_2[P(q)] \tag{2}$$

and thus, H represents the Shannon SE of the signal $x(t)$. In Equation (1) and (2) r and q are natural positives numbers related to the time, t, and the frequency axis, f, by: $t=t_s r$ and $f=f_r q$, where t_s is the sampling time and f_r the frequency resolution. The energy of the signal is instead defined by the well-known relation: $E = \sum_r |x(r)|^2$. Since entropy, as stated previously, can be affected by the presence of the seismic input, in the present paper we analyze the trend of H with respect to E for each seismic event. As can be seen in Figure 3, H can be fitted by a linear law in the $ln(H/E)$-$ln(E)$ plane:

$$ln(H/E) = a\, ln(E) + b \tag{3}$$

The linear law becomes a power law in the H-E plane:

$$\begin{gathered} H = B_E\, E^{1+a} \\ B_E = exp(b) = H/E^A \end{gathered} \tag{4}$$

In Equations (3) and (4), a and b are the fitted parameters of the linear law in the $ln(H/E)$-$ln(E)$ plane; while $(1+a)$ and B_E are the shape and scaling factors of the power law $H(E)$, respectively. Since the indicator B_E can be seen as a normalized SE with respect to a power law of the energy, it is also less sensitive to the presence of a seismic input. B_E also provides information of the order/disorder of the records along their energy value. The higher B_E, the higher the disorder of the records for different energy values. The M records (number of channels) have been used to perform the fitting of the n-th seismic event. In a continuous monitoring of the buildings, B_E becomes a function of the seismic events, $B_E=B_E(n)$. If we consider the event $n=1$ as the reference configuration of the structure, $B_{Er}=B_E(1)$ is assumed to be the reference entropy indicator and it can be used to assess the evolution of the damage by studying the normalized difference between $B_E(n)$ and B_{Er}:

$$D(n) = \frac{B_E(n) - B_{Er}}{B_{Er}} \tag{5}$$

In Equation (5), $D(n)$ is the damage index for the event n. A positive value of D indicates the occurrence of damage in the analyzed building with respect to the reference configuration.

3. Case studies

The recent earthquakes that struck Italy highlighted the vulnerabilities of masonry buildings, [6-9]. In this Section, the SE is applied to monitored buildings in order to detect the damage that occurred during the various seismic events of the central Italy earthquakes. The selected buildings are the Court of Fabriano (AN), the Town Hall of Pizzoli (AQ) and the School of Visso (MC). All the buildings are part of the network of strategic buildings monitored by the OSS. The OSS, is a nationwide network founded by the Italian *Dipartimento della Protezione Civile* (DPC) in the 1990's. The aim of the OSS network is to monitor various strategic Italian buildings, such as bridges, schools, hospital, and city halls, [10].

Starting from August 2016 a large seismic sequence struck central Italy. Between August 2016 and January 2017 there had been 9 seismic events with a magnitude higher than 5.0. In more detail, the earthquake that struck this area on October 30, 2016 (06:40 UTC) had a magnitude of 6.6, [11], which is the largest earthquake in Italy since the Irpinia earthquake that struck southern Italy in 1980 with magnitude 6.9. The buildings analyzed have a mixed brick-stone masonry structure and were built between the 1920s and 1940s. Two of them had already been damaged in a previous seismic event. The Town Hall of Pizzoli was slightly damaged in the L'Aquila earthquake in 2009, while the school in Visso was damaged in the Umbria-Marche earthquake in 1997. But only the school was retrofitted with strengthening interventions, [12]. The building that host the Court of Fabriano is equipped with 31 accelerometers. The dynamic monitoring system installed on the Pizzoli Town Hall, instead, is composed by 17 accelerometers, [13]. While, the one installed in the school building in Visso counts 23 accelerometers, [12].

(**a**) (**b**) (**c**)

Figure 1. The three case studies: (**a**) Court of Fabriano; (**b**) Town Hall of Pizzoli; (**c**) School of Visso.

(**a**) (**b**) (**c**)

Figure 2. Some damages observable after the seismic sequence: (**a**) Fabriano; (**b**) Pizzoli; (**c**) Visso.

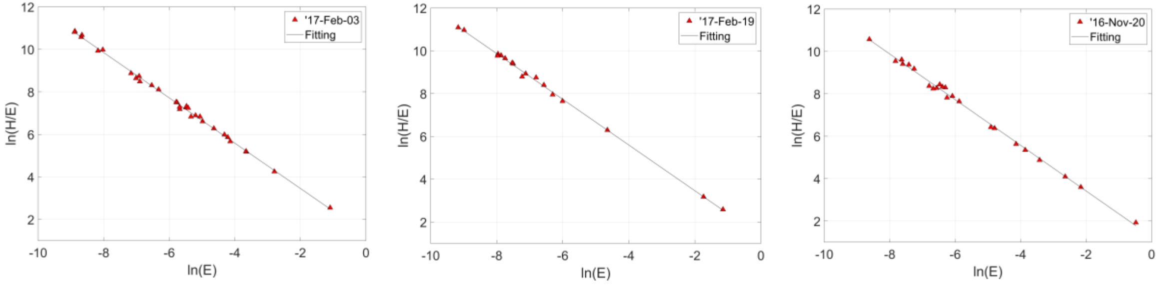
Table 1. Available main shocks and related PGAs of the buildings (*x*: major axis of the building, *y*: minor axis of the building, *z*: vertical axis of the building).

Main shock	Building	PGA-*x* [g]	PGA-*y* [g]	PGA-*z* [g]
2016-Ago-24a (01:36 UTC)	Fabriano	0.04	0.05	0.03
	Pizzoli	0.08	0.09	0.06
	Visso	0.33	0.32	0.13
2016-Oct-26a (17:10 UTC)	Fabriano	0.03	0.03	0.02
	Pizzoli	0.02	0.02	0.02
	Visso	0.29	0.21	0.41
2016-Oct-26b (19:18 UTC)	Fabriano	0.08	0.09	0.08
	Pizzoli	0.02	0.03	0.02
	Visso	0.36	0.48	0.31
2016-Oct-30 (06:40 UTC)	Fabriano	0.05	0.04	0.05
	Pizzoli	0.11	0.11	0.06
	Visso	0.29	0.30	0.33
2017-Jan-18b (10:14 UTC)	Fabriano	0.01	0.01	0.00
	Pizzoli	0.11	0.10	0.08
	Visso	-	-	-

Figure 1 and Figure 2 show the three buildings and the observable damage after the seismic sequence, respectively. The OSS permanent monitoring systems allowed the recording of the seismic response of the three masonry buildings before and during this seismic sequence. The available main shocks of this seismic swarm are reported in Table 1, together with the Peak Ground Acceleration (PGA) recorded at the base of each building in the three orthogonal directions.

4. Results and Discussion

The methods introduced in Section 2 are here applied to the buildings described in Section 3. As can be seen in Figure 3, *H* follows a linear law with respect to *E* in a *ln*()-*ln*() plane. This is true for each building and for all the analyzed seismic events. The curves fit the experimental data (centered to 0-mean and scaled to 1-variance) in a least-squares sense. The results of the fitting procedure are reported in Table 2.



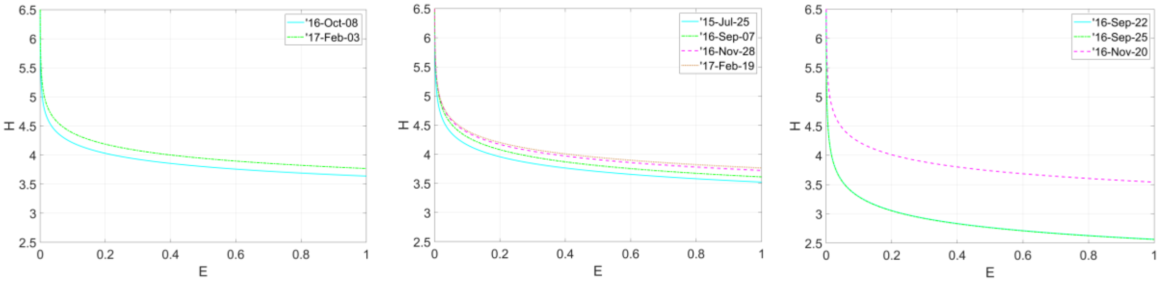
(**a**) (**b**) (**c**)

Figure 3. Fitting, in the *ln*()-*ln*() plane, of the experimental data for the building of: (**a**) Fabriano, mild seismic event of the 2017-Feb-03; (**b**) Pizzoli, mild seismic event of the 2017-Feb-19; (**c**) Visso, mild seismic event of the 2016-Nov-20.

Table 2. Parameters, *a* and *b*, of the linear laws.

	---- Fabriano ----		----------------- Pizzoli -----------------				------------ Visso ------------		
Seismic event	2016	2017	2015	2016	2016	2017	2016	2016	2016
	Oct-08	Feb-03	Jul-25	Sep-07	Nov-28	Feb-19	Sep-22	Sep-25	Nov-20
a	-1.063	-1.065	-1.072	-1.075	-1.070	-1.068	-1.108	-1.108	-1.077
b	1.291	1.326	1.259	1.284	1.314	1.325	0.942	0.941	1.265

It is now possible to analyze the power law curves of the seismic sequence for the case studies. In Figure 4 it is possible to note how with the proceeding of the seismic sequence, the curves tend to higher values of *H*, in accordance to the occurrence of strong earthquakes during the analyzed period (from 2016-Ago to 2017-Feb) which may have damaged the three buildings. In Figure 4(**c**) it is also possible to note how the building of Visso exhibits the greater difference between the reference curve (2016-Sep-22), and that one at the end of the seismic sequence (2016-Nov-20). The entropy indicator, B_E, is then depicted in Figure 5.

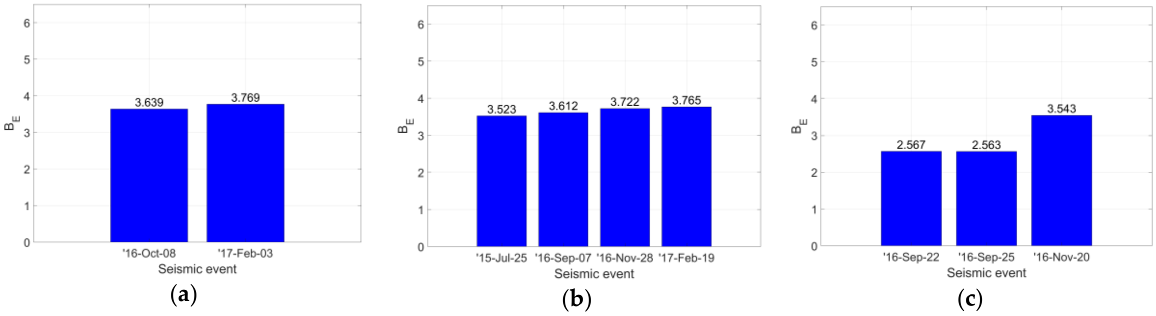


(**a**) (**b**) (**c**)

Figure 4. Power law curves, in the *H*-*E* plane, of the seismic sequence for the building of: (**a**) Fabriano; (**b**) Pizzoli; (**c**) Visso.

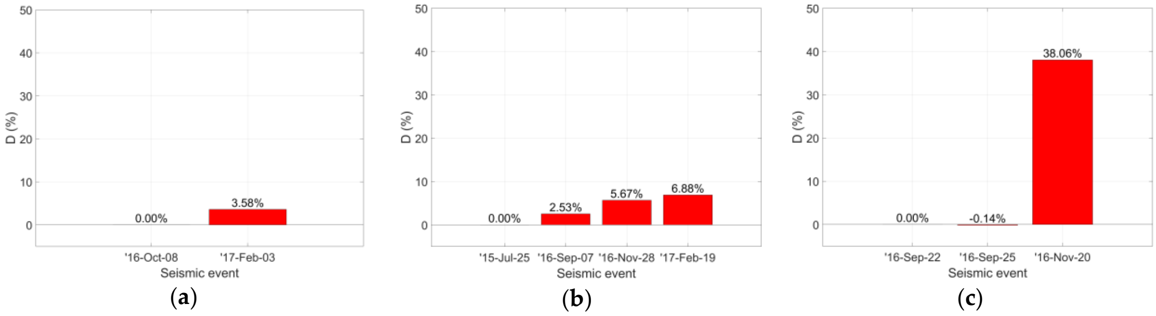
It is worth noting that the three buildings exhibit a very different results in terms of B_E. In more detail, the building of Fabriano is characterized by an almost constant B_E. The Town Hall of Pizzoli instead, exhibits a constant growing trend, while in the case of Visso a strong increase of B_E is depicted between the 2016-Sep-25 and 2016-Nov-20.

Using Equation (5), is then possible to calculate the damage index, *D*, of the three buildings. The index is represented in Figure 6. Since *D* follows the trend of B_E, also in this case the three buildings exhibit very different results. For Fabriano, the damage index increases of about 3.58% after the seismic sequence. Nowadays the building is operating regularly and open to the public. No important damage was detected on the structure following the seismic sequence (from 2016-Ago to 2017-Feb) (Figure 2(**a**)), thus the building was considered safe. For the building in Pizzoli, the damage index constantly grows reaching the 6.88% at the end of the seismic sequence. It is important to note that the Town Hall of Pizzoli was affected by various main shocks between each analyzed mild event. The main shocks occurred on 2016-Ago-24a/24b, 2016-Oct-26a/26b, 2016-Oct-30, 2017-Jan-18a/18b/18c/18d and the main increment in *D* (about 3.14%) occurred between 2016-Sep-07 and 2016-Nov-28, thus after the main shocks of 2016-Oct. The building was temporarily closed after the seismic events for a slight damage in the inner walls (Figure 2(**b**)). Finally, in the case of Visso, the damage index between the 2016-Sep-22 and 2016-Sep-25 is almost nil, in accordance to the fact that between those days did not occurred any seismic event. On the contrary, a strong increase of *D* is found with the mild event of 2016-Nov-20 (after the main shocks of 2016-Oct). It is known that after the main events of 2016-Oct the building of Visso showed severe and widespread damage in the entire structure. The *D* index reached the 38.06% at the end of the seismic sequence. Since then (see Figure 2(**c**)), the building is closed for safety reasons.



(**a**) (**b**) (**c**)

Figure 5. Entropy indicator, B_E, of the seismic sequence for the building of: (**a**) Fabriano; (**b**) Pizzoli; (**c**) Visso.



(**a**) (**b**) (**c**)

Figure 6. Damage index, *D* [%], of the seismic sequence for the building of: (**a**) Fabriano; (**b**) Pizzoli; (**c**) Visso.

5. Conclusions

In the present study, the damage detection of three masonry buildings affected by the central Italy earthquakes in 2016 has been pursued by means of Spectral Entropy, using the Shannon entropy measure. Since the entropy level can be compromised by the seismic input, an entropy indicator that provide information of the order/disorder of the system at various levels of the signals' energy is proposed. The damage index, *D*, calculated by using the entropy indicator, B_E, provide results in accordance with the observed damage in the buildings and with the evolution of the seismic sequence for all the case studies. A drawback of the method is due to the fact that it can be used only far away from strong seismic events (more than a week), which can temporarily compromise the estimation of the damage index, probably due to the seismic wandering effects. As for future works, an instantaneous estimate of the entropy indicator, B_E, could help in providing real-time information on the health state of the structure.

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Author Contributions: Rosario Ceravolo is the head of the local unit of ReLUIS and supervised the work; Erica Lenticchia did the introduction, defined the framework of the spectral entropy and its applications, and introduced the case studies; Gaetano Miraglia performed the analyses and discussed the results.

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