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An Empirical Method to Assess the Seismic Vulnerability of Existing Buildings Using the HVSR Technique

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Abstract—The seismic vulnerability of existing buildings is usually estimated according to procedures based on checklists of main structural features. The relationship with damage is then assessed using experience from past events. An approach used in seismology for the evaluation of site amplification, based on horizontal-to-vertical ratio of weak motion and microtremors, has been applied to the structural field. This methodology provides an alternative, promising tool towards a quick and reliable estimate of seismic vulnerability. The advantages are:

- The measurements are quick, simple and stable. They are non-invasive and do not affect at all, even temporarily, the functions housed in the buildings studied.
- The site effect and the soil structure interaction are explicitly accounted for in the vulnerability estimate, when they are excluded in the traditional approaches.
- The relationship with damage is established using meaningful physical parameters related to the construction technology, instead of adimensional, normalised indexes.

The procedure has been applied to several case histories of buildings damaged in the recent Umbria–Marche earthquake which occurred in Italy in 1997. The same model has been applied to different structures (brick/stone masonry and infilled r.c. frames), on different geological conditions and under very different seismic loads. Using this combined site/building approach, it was possible to explain very sharp variations in the damage pattern.

Key words: Microzonation, Umbria–Marche earthquake, vulnerability, HVSR, microtremors.

Introduction

The structural vulnerability of a building subjected to an earthquake is generally related to the capability of its structural members to maintain a certain degree of integrity which should be constant, at least for the same typologies of buildings in the same area.

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Recent studies on large building groupings carried out on the damaged heritages in Central Italy after the earthquake of September 1997 as well as in Slovenia and Basilicata, Italy after the 1988 events (MUCCIARELLI and MONACHESI, 1998, 1999; MUCCIARELLI *et al.*, 1999) have shown how both the site effect and the structural frequency have a crucial effect on the induced damage. Many houses with clear seismic design deficiencies withstood high intensity motions, where infilled r.c. frames showed deep damage. Moreover, adjacent buildings in highly dense villages showed very different damage patterns according to the variation in the respective soil properties and foundation technologies.

Contrastingly, the vulnerability studies have become very urgent in the areas where very large heritages have been constructed in the past with no seismic concept: the correct management of any strengthening action today, strongly requires a robust quantitative approach in order to reliably organise the very high investments required, assigning precise priorities to the most vulnerable buildings.

The site effect contribution to the map of damage distribution is a very well known effect, however its relationship with the local geology (sometimes exceedingly complex and even unknown) and with the construction technology of the buildings is quite difficult to predict by analytical methods because of the very high uncertainties involved. Therefore, the above cited evidence suggested the formulation of a global approach, *a posteriori*, to the analysis of the vulnerability of existing buildings which summarises the very complex interaction of many factors usually studied in different disciplines and avoids complicated and expensive local analysis.

The weakness of this approach is certainly the limitation to specific typologies of structures where the failure mode can be easily detected, although an extensive application of the concepts described below has shown a global general applicability with a final reliability comparable or higher than detailed numerical or experimental approaches. The two main contributions to the damage addressed in the methodology are therefore described in the following:

1. *Site amplification effects*: The variation of the input motion at the basement of the building due to the propagation of the seismic waves in a layered soil is a very well known effect, but the evaluation of its effect on the single building is very difficult, especially on existing towns where also the mutual interaction between buildings and the presence of the construction can influence the pure soil analysis. In areas where the geology is complex, the forecasting of the true input to be expected could be even more complicated.

2. *Building stiffness and mass distribution*: The evaluation of the true building properties is almost impossible, especially in old constructions, and therefore any evaluation of the mathematical properties to be used for retrofitting design is affected by enormous uncertainties. Recent applications of fuzzy logic and artificial intelligence to the very rigid methodologies of the vulnerability indexes (GAVARINI and PADULA, 1994) are trying to bypass the intrinsic disadvantage of these

methodologies, although major uncertainties remain in the influence of critical parameters, such as soil structure interaction, which cannot be included in such tools.

The result of the interaction between the cited factors should nonetheless be treated in a dynamic framework and this requirement makes a potential analytical study increasingly difficult: evidence showed in fact very different resulting damage on similar houses, even adjacent, on different soil conditions. The amplification effect due to the proximity of the first natural frequencies of the structure and the frequency range of the input spectrum with the highest energy content has shown to be crucial. Furthermore, the evaluation of the natural frequencies of a building is even more uncertain than the evaluation of its static properties, suggesting alternative approaches to the retrofitting engineers, different from the traditional analysis of structural members.

The proposed procedure, essentially based on a few microtremor measurements on the floors of the existing building, is actually an application of the measuring technique set up by NAKAMURA (1989) for site effects and then extended to the specific construction typologies. This methodology advantageously exploits specific properties of the measured structures in the filtering of the signals, avoiding the typical dependency of ambient vibration measures from the spectrum of the applied vibration (wind, traffic, etc.)

In this context however that technology is applied to common buildings and the results processed with special criteria directly related to very simple structural behaviour hypotheses. The first application by Nakamura himself of the method (NAKAMURA, 2000) in fact has been developed with reference to a so called amplification factor between soil level and the various floors, and a corresponding threshold has been set up to this parameter. This work presents a different theoretical background, attempting to fix an absolute threshold on story drift and lateral deflections, according to the last experimental works carried out for example in BENEDETTI and PEZZOLI (1996), where most of the damage reflects a correlation with a displacement limit. The thresholds are therefore related to the construction technology and in some cases a fine experimental tuning is required on true buildings, but with a very high probability of success when the procedure is applied to similar situations.

The following chapters present the two main ingredients of the procedure: The measurement technique and the structural failure model, coupled with the soil amplification approach applied in the case study described in the final chapter, related to the last earthquake sequence which occurred in Marche and Umbria (central Italy) starting September 1997.

The HVSR Technique

The signals used were recorded with a tridirectional sensor Lennartz 3D-Lite (1 Hz period), connected with a 24-bit digital acquisition unit PRAXS-10 and a personal computer board 486 100 MHz. The sensor has the same characteristics on the three axes.

The site transfer functions were computed as follows: First a set of at least 5-time series of 60 s each, sampled at 125 Hz, were recorded. Time series were corrected for the baseline and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal and bandpass-filtered from 0.1 to 20 Hz, with cut off frequencies at 0.05 and 25 Hz. Fast Fourier transforms were applied in order to compute spectra for 25 predefined values of frequency, equally spaced in a logarithmic scale between 0.1 and 20 Hz, selected in order to preserve energy. The arithmetical average of all horizontal to vertical component ratios were taken to be the amplification function. Full details of the methodology and its limits are given by MUCCIARELLI (1998).

The Failure Model

The development of a failure model strongly relies on two items:

- The construction technology (frames, infill frames, masonry buildings, etc.): in this context of requalification, special emphasis will be given to traditional technologies, such as masonry and infill frames which cover most of the traditionally designed buildings in the seismic regions of Southern Europe;
- The degradation of the structural properties after a cyclic action: many attempts were carried out in order to correlate the structural dynamic response to the safety margin of a structure. In this context reference will be made to current properties at the measuring time, leaving to further studies the required extrapolation studies.

The main difficulty in establishing a threshold for the damage indicator is related to the definition of damage itself: in CORSANEGO (1994) a favorable review of the most adopted concepts suggests a definition of damage at building, storey, member level respectively and, furthermore, based upon structural and/or economic criterion. In this context only a structural evaluation could be correlated to the proposed measurements and in the following explicit reference is made only to structural stability. Of course the criterion can be tuned in order to also represent intermediate damage steps with an associated estimate of repairing investments.

Large experimental campaigns on masonry buildings have shown that the damage in the structural members can easily be correlated with the inter-story drift (IDI). In fact the structural failure of commonly designed buildings is associated with the collapse of bearing walls, the collapse of the frame and the collapse of infills which contribute to the dynamic stability: all of them are approximately related to an IDI value ranging from 0.004 up to 0.05 (TERAN *et al.*, 1995).

The observed damage on true buildings actually confirms these common feelings, fixing at about 0.004 the threshold. This value should be further evaluated in order to consider the true safety margin for the structure:

- in the case of infill frames, damage in the frame leads to the sudden collapse of the building;
- in the case of weak infills, their damage leads regardless to their sudden explosion with consequent service limit for the building;
- in the case of masonry building, the degradation of the masonry properties can in some cases lead to a smooth transition into the unsafe area, leaving additional margins, as pointed out in many critical studies (BENEDETTI and LIMONGELLI, 1996).

The problem has been intensely studied, both with physical and statistical approaches, and extensive references are provided in BENEDETTI and LIMONGELLI (1996) and CALVI (1999).

The proposed approach is therefore a double correlation between the transfer function, measured according to the procedure described above, times the expected site acceleration (including the site effect) and the amplification threshold plus the peak frequency range.

Therefore the evaluation of the interstorey drift is carried out through the calculation of the horizontal displacement between two floors (u_n and u_{n-1}), and therefore it can be written as

$$\mathrm{IDI}(\omega) = u_n - u_{n-1} = \left[1/\omega^{2*}(F_n - F_{n-1}) * i_s * i_E\right]/h \ , \tag{1}$$

where ω is the frequency, F_n is the acceleration transfer function evaluated with the HVSR technique at the n-th floor, i_s is the site amplification (evaluated with the same HVSR technique with a measurement on the site free field), i_E is the expected acceleration from the earthquake at the bedrock below the site (generally calculated with attenuation relationship from the expected epicentre or by statistical considerations), h is the inter-storey height (or more generally the height between the measurement point of F_n and F_{n-1}).

This formula can be applied to the HVSR measurements for the calculation of the functions IDI to be compared with the expected excitation on the specific site. Some assumptions are implicit in the formulation:

1. The soil structure interaction effect in a rocking degree of freedom does not affect significantly the estimate of the reference acceleration at ground level: in fact the estimate of the site effect can be quite difficult in the presence of the building, however relying on the general height-versus-base ratio of common buildings, most of the interaction effects are referred to lateral shear displacement and the measurement at the first floor can be representative.
2. The structural damage is only associated with lateral storey drift and disregards many other failure mechanisms related to vertical excitation, out of plane failure, etc.: in this sense the model is definitely limited to conventional buildings, designed with conventional criteria and seeks not to be too general. The entire HVSR technique presented above therefore has an implicit assumption on the failure mode: the collapse of the infills for the service limit states, the shear collapse mode for the global failure of the building.

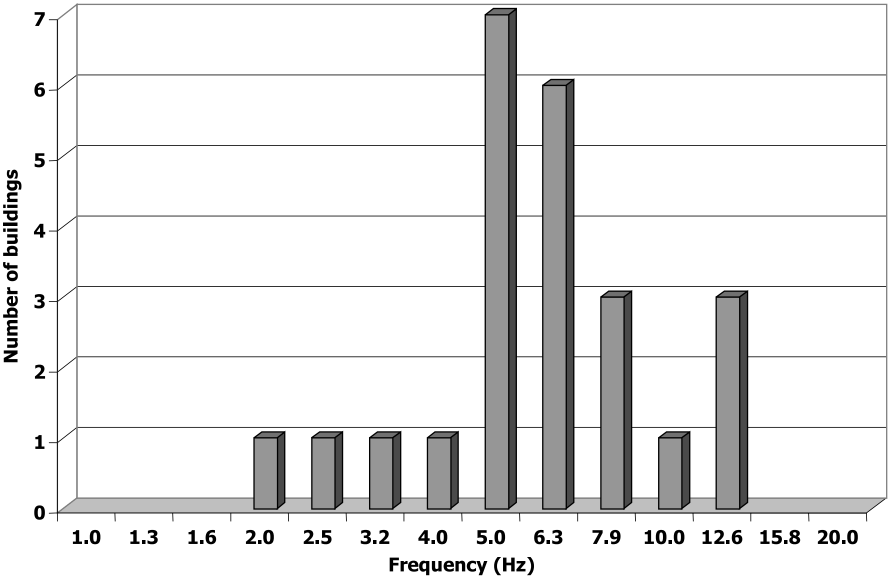

Figure 1
Distribution of resonance frequency for the buildings in the town of Fabriano.

3. The extrapolation of the true structural response during an earthquake from the ambient vibration analysis is usually criticised in the experimental tradition where the application of a large and harmonic excitation is preferred. The low amplitude of the exciting signal could in fact in principle exclude the nonlinear effects, coming essentially from soil. However, it is common judgement that the nonlinearities introduce similar shifting both in the excitation and in the structural response, leaving a value regardless to the comparison of the two quantities, even if carried out at a low amplitude (ŠAFAK, 1995).

The most critical aspects are related to the nature of the excitation: usually microtremors on buildings are referred to ambient actions, essentially wind and traffic which act on the structure in a frequency range typically different from the earthquake. The filtering method proposed in the HVSR technique should exclude the effect of the spectrum of the forcing action on the response spectrum, therefore assuming a type of white noise as input function. In this sense the measured transfer function could only be considered representative of the structural response.

The proposed formula could be applied floor by floor, gaining the expected maximum deformation of the building, however a selected application is recommendable respectively at the ground floor, at the first floor, where the shear strain normally is accumulated, and at the top of the building, where the maximum total deflection is regularly recorded, provided the inter-storey height is constant and the structural design is homogeneous.

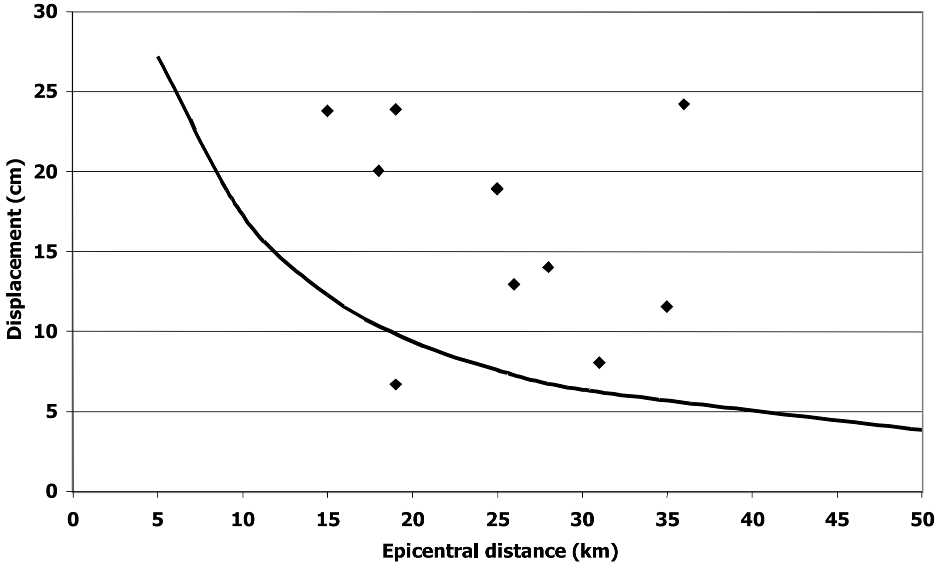

Figure 2
Attenuation relationship for horizontal displacements at bedrock (line) with displacement expected at the sites of Figure 3 (diamonds; see text for details).

The resulting curve, obtained from the application of the proposed formula to the measured transfer function, should be compared with the expected earthquake spectrum on the site; certain situations can arise:

1. The highest peaks of the two curves fall within the same frequency range and the amplification is higher then the threshold: in this case, according to the evidence collected in the measuring campaigns by the authors, the building should be retrofitted.
2. The peaks, though quite high, fall within different frequency ranges: the building is vulnerable, nonetheless the expected earthquake should not damage it.
3. The peak frequency range of the two curves is different and the structural response has peaks lower than the threshold: the building should properly withstand the expected earthquake.

A degree of vulnerability can therefore be associated with any building of interest with at least three measurements (5–10 minutes each plus 15 minutes for processing and storage): the results can then be plotted on a map of the area of interest and correlated with economical indexes for a final optimisation of the retrofitting efforts. Examples are shown in the next section.

This procedure has also been deemed very useful in the case of implementation of retrofitting actions: a comparison of the structural response before and after the retrofitting can provide a quantitative measure of the benefit introduced.

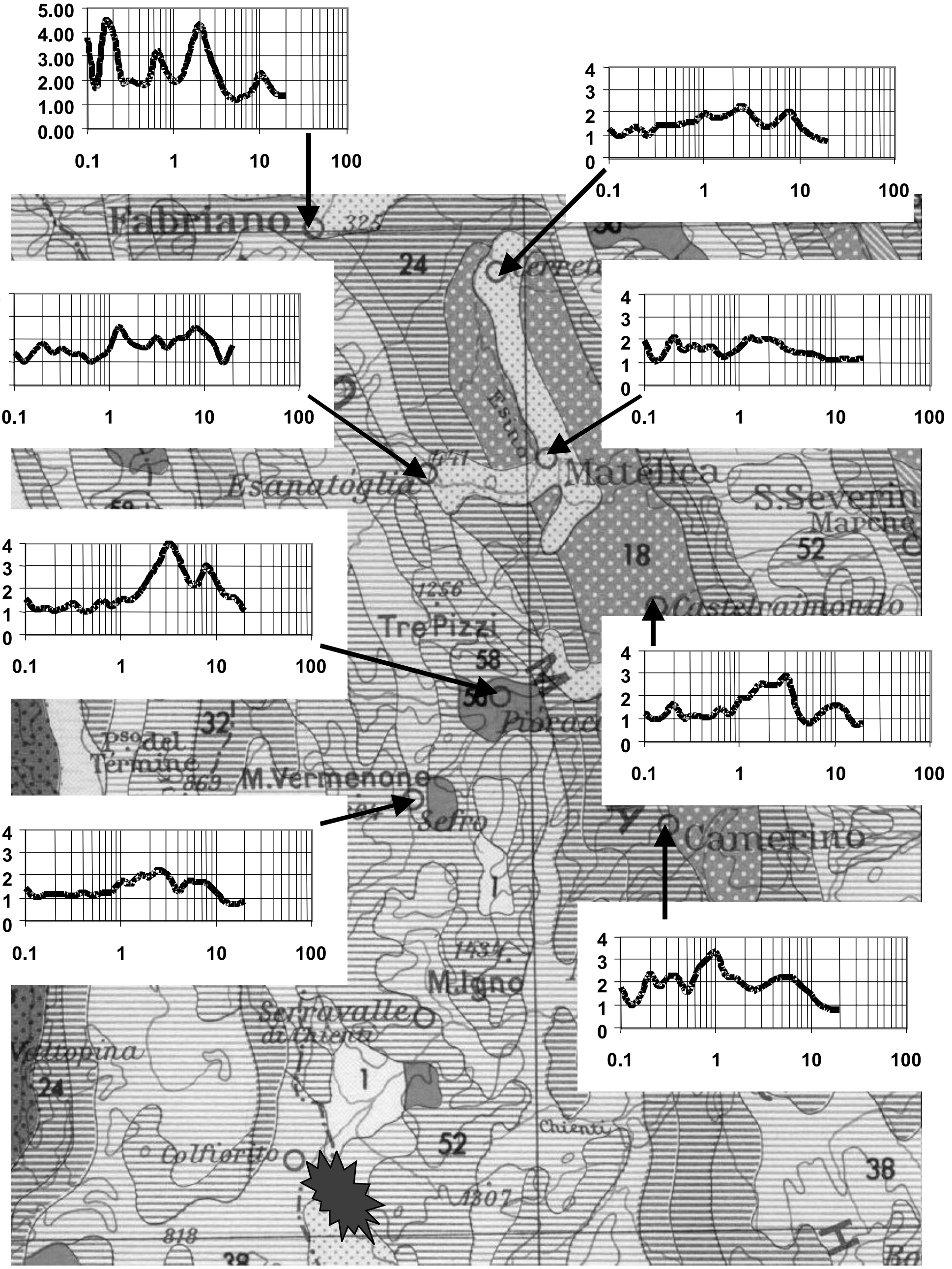

Figure 3
Site amplification function for the towns North of the epicentral area of the Umbria–Marche 1997 main shock.

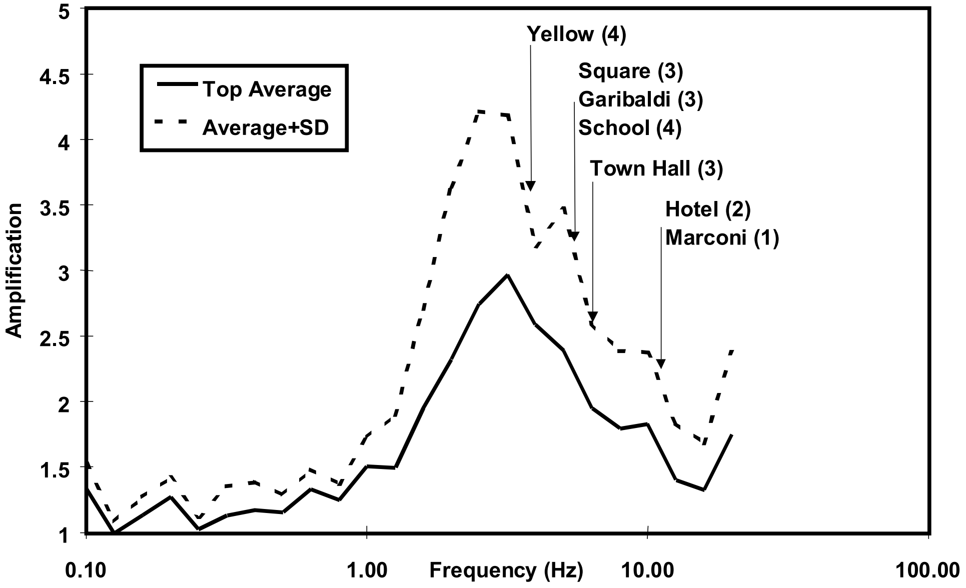

Figure 4
Average site amplification on the top of Sellano hill with superimposed resonance frequency of buildings (arrows) and EMS damage (in parentheses).

Case Studies

The earthquake sequence that struck the Umbria–Marche region began during the night spanning 25 and 26 September 1997. The main shock reached $M_w = 6.0$. Until October 15 there were 7 shocks exceeding magnitude 5 (EKSTRÖM *et al.*, 1998).

The damage pattern was complicated by the fact that the large aftershocks augmented the damage on several buildings. Moreover, the sequence spread NW and SE with respect to the epicentre of the first two shocks, and therefore it was impossible to consider a simple scheme according to the epicentral distance. The areas and the buildings selected for the study were examined as soon as possible after the event that caused more damage, and as such ensuring that there was a single event responsible for most of the observed effects.

The case study presented here regards, 1) R.C. buildings in the town of Fabriano, 2) the damage in the town of Sellano, 3) Overall consideration of the measurement performed. In Fabriano, 35 km from the epicentre, a group of R.C. buildings were damaged to the extent that the evacuation of inhabitants was necessary. A large microzoning project was undertaken, also with the deployment of a dense weak-motion array. The measurements of building frequency were originally aimed to identify possible interference of building vibrations on weak-motion recordings. The measurements performed showed that the frequency of the most damaged 5-storey

Table 1

List of the buildings examined for the correlation between expected IDI and observed damage

Town	Type of structure	EMS Damage degree
Sellano	Masonry + RC without ASD	4
Fabriano	RC with brick infills	4
Sellano	Stone masonry	4
Fabriano	RC with brick infills	3
Sellano	Stone masonry	3
Sellano	Stone masonry	3
Sellano	Stone masonry	3
Esanatoglia	Stone masonry	2
Sellano	RC with brick infills	2
Fabriano	Brick masonry	2
Sellano	Concrete block masonry	1
Fabriano	RC with brick infills	1
Matelica	Brick masonry	1

building was about 2 Hz, and the free-field soil frequency also showed a peak at about 2 Hz. Figure 1 shows the distribution of frequency for the 24 buildings that were examined in the town of Fabriano: it can be seen that there is only one resonating at 2 Hz. In the epicentral area there were very few R.C. buildings, and all were less tall than the studied one.

In Figure 2 the standard attenuation relationship for horizontal displacements at bedrock for Italy is superimposed on the displacement expected at the sites of Figure 3 multiplying the attenuation function by the measured transfer function at each site. The high value at 35 km epicentral distance corresponds to the Fabriano neighbourhood where the damage was observed. It can be noted that such an high site effect corresponds to the displacement expected in this range of frequency at only 5-km epicentral distance. Figure 3 shows the amplification measurements made with Nakamura's technique in several sites on the alignment from the epicentral area toward Fabriano. It is clear that Fabriano has the largest amplification, especially around 2 Hz. This may explain the observed damage enhancement as a resonance effect between soil and building frequency.

For Sellano, measurements were made in several buildings at a different level of damage. Figure 4 reports the average amplification function measured for the town together with the dominant frequency for the buildings studied and the damage level observed according to EMS-92. The ground-motion amplification in the town is mainly due to a hill-top morphological effect, with variability due to the presence of anthropic fills.

It is clear that the damage is greater to buildings whose frequency approaches the site transfer function. Moreover, it is worth noting that the vulnerability assessed with the traditional method is completely uncorrelated with the damage observed:

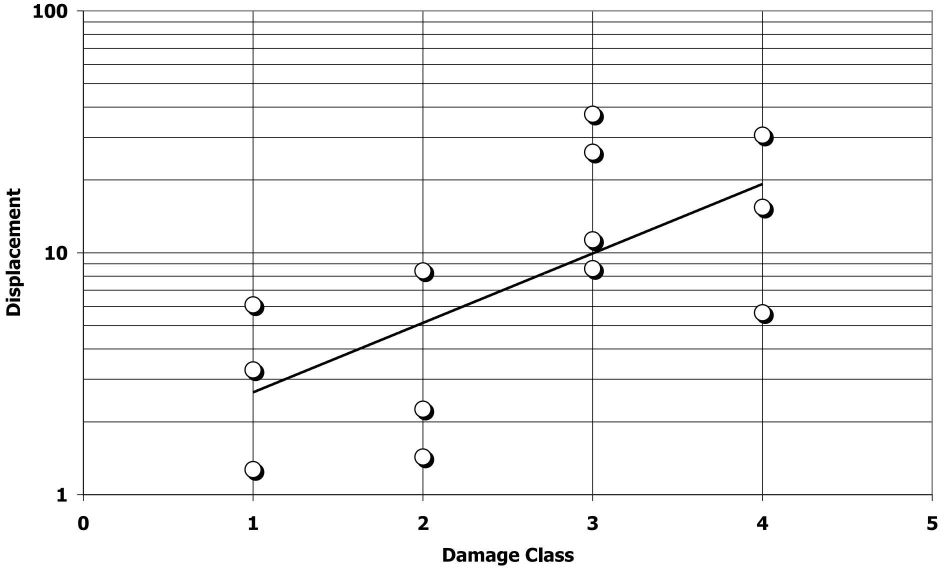

Figure 5
Correlation between damage and calculated IDI (Inter-storey Displacement Index). The displacement is in cm. To obtain the normalised IDI, it should be divided by the average inter-story height, i.e., 300 cm.

the building labelled Marconi is an *L*-shaped block-masonry building, while Yellow was retrofitted with ASD after an earthquake occurred in 1979.

Lastly, a general correlation is sought between the IDI calculated according to the formula (1) and the damage observed in all the buildings studied. The list of the studied buildings is reported in Table 1: these 13 buildings are those for which it was possible to collect data both on free field and at different stories. Figure 5 reports the result of this analysis. The separation between non-structural damage (classes 1 and 2 of EMS) and structural damage (from class 3 on) could be tentatively placed at 10 cm for an average storey height of 3 m (IDI $= 0.033$). This value appears higher than those reported in the literature and mentioned above. It should be noted that we are not referring to the onset of damage, which may occur at lower values, rather to the onset of structural damage that may result in the terminal loss of the building (due to the need for repair intervention with unfavourable cost balance). The intercept for damage $= 0$ of the straight line superimposed to the data is 1.3, which corresponds to IDI $= 0.004$. The fit is encouraging, and we plan to collect more data after the occurrence of future earthquakes. Correspondingly, we are planning shaking table tests to quantify the variability of fundamental frequency as a function of damage class. Finally, we hope in the future to have enough data to be able to separate at least the two main typologies of masonry and RC buildings.

Conclusions

The proposed methodology has been thoroughly tested during the earthquake sequence in Umbria–Marche on a set of buildings pertaining to very different construction technologies and local soil conditions.

The HVSR ratio has proved to be an effective method for structural dynamical analysis using earthquakes (CASTRO *et al.*, 1998). The extension of this methodology to the use of microtremors enables us to carry out studies at any time without the need to wait for a seismic event and without the need for permanent and costly instrumentation. There is an ongoing debate within the seismological community on the nature of the seismic waves which produce the effects measured with Nakamura's approach, and some scientists are not satisfied with current theories. However, this does not apply to the proposed procedure which aims to consider the damage caused by the first shear and bending modes of a building by directly measuring the shear displacement and inter-storey drift.

Both single case histories are difficult to understand with traditional approaches and the overall damage pattern can be satisfactorily explained by the proposed approach. It is useful noting once more that it is non-invasive and does not affect, even temporarily, the functions housed in the buildings studied: it requires very little time and thus is suitable not only for post-event studies but also for planning pre-emptive measures. It would be possible to optimise on a priority scale the resource allocation for seismic retrofitting of urban nuclei, as well as to provide information useful to civil defence authorities and the insurance companies.

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