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VIBRATION MONITORING OF AN EXISTING MASONRY BUILDING UNDER DEMOLITION

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SUMMARY

The loss potential of earthquakes is substantial even for sites of moderate seismicity, due to the disastrous consequences of rare events. Large parts of the existing European building stock, mainly masonry structures, do not fulfil the current seismic standards, while many buildings have long exceeded their design lifespan. Given the inherent uncertainties of masonry as a composite material, unknown effects of ageing, and the corresponding difficulty to estimate the nonlinear response of such structures, data-driven health monitoring provides an efficient way to reduce epistemic uncertainty and to derive damage-sensitive features for structural assessment after strong ground motions. In this study, vibrational recordings during the demolition of a real masonry building have been analyzed. The accumulating damage during demolition provides a valuable insight into the correlation between dynamic response and structural health. The findings shed light on the performance of a typical masonry structure, built in the 19\textsuperscript{th} century, under non-conventional loading and form a step towards the definition of damage-sensitive features based on real data.

Keywords: vibration measurements, operational modal analysis, historical masonry building, damage detection, demolition monitoring

1. INTRODUCTION

The seismic assessment of existing structures comprises a major challenge that brings together practicing engineers and the academic society. A large part of the existing infrastructure and buildings has been constructed before seismic, or even structural, design codes and standards were established. Thus, numerous assumptions have to be considered for the estimation of the safety margins according to the current norms. Non-standardized materials, incomplete documentation, unknown effects of ageing and unclear (and potentially changing) boundary conditions inflate the uncertainty in performance predictions. Despite advances in processing and simulation capabilities, the reliability of the evaluation of existing structures cannot be increased effectively without additional structural information.

Nowadays, the rapid development in sensor technology allows engineers to gather huge amounts of data from real structures. Although potentially informative for designers and researchers, large measurement databases are not easy to manage and require knowledge in a wide spectrum of disciplines. System-identification methods, nonlinear structural dynamics and data analysis should be implemented in order to make use of the available information. While dynamic measurements are often considered costly for the assessment of common building structures, they inevitably resurface as unexploited potential after catastrophic events. To this end, several researchers have shown that operational modal analysis (OMA) provides an elegant and cost-effective way to reduce building-behaviour uncertainties by measuring the global dynamic structural response under ambient excitation ([1], [2]). Although OMA is conducted under very low excitation amplitude, and therefore under an elastic regime, the derived structural properties reduce the uncertainties in the equivalent elastic range. This eventually benefits the assessment of the response in the nonlinear range through nonlinear models [3], or according to formulations that link nonlinear to linear parameters, as available in current standards [4]. Snoj et al. [5] have highlighted, through a parametric study, the importance of the identified elastic properties of existing structures for the accurate assessment of ductility. To what concerns variation of the elastic properties, experimental findings have confirmed that for response amplitudes ranging between $10^{-5}$ g and $10^{-2}$ g, the identified elastic properties do not show significant variability [6], [7]. Consequently, ambient vibration tests...
are sufficient to identify the structural behaviour in the equivalent elastic domain and contribute to the reliable assessment of the global ductility. Nevertheless, full-scale measurements capturing the nonlinear response of buildings, though very scarce in the literature, are invaluable for the understanding of the post-elastic behaviour of structures. Particularly in sites characterized by long return periods of strong ground motions, the lack of recent events prevents the realistic assessment of the seismic performance, while leading to the erroneous perception that low seismic hazard translates to low seismic risk [8]. Hence, designers base their assumptions exclusively on guidelines that provide wide ranges for the elastic properties leading to unreliable and often unrealistic and non-conservative results.

In this contribution, important insights into nonlinear response are obtained through vibration measurements during the demolition of a full-scale masonry building. The possibility to correlate real damage scenarios with anomalies in the records is valuable for the development of damage-sensitive features. On an urban scale, sorting the examined from a structural perspective facilitates the extrapolation of the findings to building categories with similar typological features. The scope of this work lies in exploring the potential use of vibrational and visual data obtained during the demolition of a typical masonry building, to further inform the seismic reliability assessment of existing structures. In addition, the investigation of associated global and local damage indicators comprises a first step towards efficient and robust damage detection and localization in existing masonry buildings after strong ground-motion events.

![Examined building and sensor location.](image)

**Table 1. Mechanical characteristics of the sensor nodes (LIS344)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Acceleration range</th>
<th>Sensitivity (typical)</th>
<th>Noise density</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS</td>
<td>± 2 g</td>
<td>660 mV/g</td>
<td>50 μg / (Hz)²</td>
</tr>
</tbody>
</table>
2. **PROJECT DESCRIPTION**

The presented case study comprises a four-storey masonry building with a basement and an attic. The external dimensions are $20.6 \times 10.4 \times 17.7$ m ($l \times w \times h$). As shown in Fig. 1, the geometry is regular and the floors consist of wooden girders. The building was erected in 1898, and experienced minor restorations up to its demolition in early 2019. The structural characteristics correspond to a rather usual structural typology of European cities with low to moderate seismicity, according to the building taxonomy of the global earthquake model (GEM) [9].

The purpose of this monitoring campaign is to capture the dynamic response of the examined building due to ambient noise, and due to the higher amplitude excitation incurred during demolition, in order to track the progressively induced damage through vibrational recordings. Major challenges are met in the implementation of low-cost sensors that could potentially be lost during the process, as well as the placement of these sensors, which should allow capturing the main vibrational modes of the building, while avoiding any potential conflicts with the demolition works. The instrumentation consists of eight triaxial accelerometers. The sensor nodes were manufactured in the IBK Laboratory, at ETH Zurich, based on the board LIS344 (ST electronics). The mechanical characteristics of the sensors are summarized in Table 1, while the sensor placement within the building is demonstrated in Fig. 1 (b, d).

3. **DATA ANALYSIS**

The initial analysis of the recorded data yielded the identification of the modal properties for the undamaged state. For the task of damage detection, four different damage scenarios (DS) have been selected (Fig. 2). DS 0 represents the undamaged state of the building and serves as reference for the subsequent damage indices. DS 1 pertains to local damage at the roof level, while DS 2 and DS 3 correspond to extensive degradation of the building’s integrity, due to wall collapses at the third and second storeys respectively.

![Damaged Building Images](image-url)  
*Fig. 2. Damage Scenarios introduced in the East side of the building: (a) DS 0, (b) DS 1, (c) DS 2, (d) DS 3*
3.1. Global modal analysis

The identified modal properties of the examined building for the undamaged state are summarized in Table 2. The fundamental mode corresponds to translation along the slender axis of the building with frequency over 3 Hz. The identification up to the fourth structural mode is succeeded through use of a Stochastic Subspace Identification methodology that relies exclusively on output recordings [10].

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Modal shape</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Translational West/East</td>
<td>3.1</td>
</tr>
<tr>
<td>2</td>
<td>Rotational</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>Rotational</td>
<td>7.1</td>
</tr>
<tr>
<td>4</td>
<td>Translational North/South</td>
<td>7.9</td>
</tr>
</tbody>
</table>

A data-based quantification of the structural degradation in a global sense is usually expressed through the frequency shift of the identified modes, or through changes of the modal shapes. In order to incorporate this information in one estimator, the following modal combined index (MCI), based on [11], is proposed.

\[
MCI^{DS-k}_{i} = \left| \frac{f_{i}^{DS-k} - f_{i}^{DS-0}}{f_{i}^{DS-0}} \right| + \left[ 1 - MAC(\varphi_{i}^{DS-0}, \varphi_{i}^{DS-k}) \right]
\]  

In Eq. 1, \( f_{i}^{DS-k} \) represents the identified frequency of mode \( i \) for DS k and, in a similar way, the Modal Assurance Criterion \( MAC(\varphi_{i}^{DS-0}, \varphi_{i}^{DS-k}) \) compares the \( i^{th} \) modal vectors of the DS 0 and DS k. As shown in Fig. 3, progressive damage affects the global dynamic response of the system. These changes can be captured even with low cost acceleration sensors that are placed in the undamaged part of the building. While the shift in measured frequencies is simple to assess, it is insufficient to conclude on the level/type of damage. The frequency drop for the first two modes is not significant (less than 5 %). In addition, for higher modes the observed frequency increases with accumulating damage and thus, provides inconclusive information, undermining the exclusive use of frequency shift as a reliable index for the damage assessment. This is expected since the induced damage affects both the stiffness and the mass distribution of the system, resulting to different frequency distortions.

The modal assurance criterion (MAC) on the other hand, adds a reliable source of information with respect to the damage level, especially for higher modes (figure 3 down). The MCI described above (see Eq. 1) integrates the information of both properties, offering adequate sensitivity for damage assessment. The index increases with accumulating damage, while it highlights the sensitivity of the higher modes to the progressive degradation of the building, as can be seen in Fig. 3.

3.2. Local signal analysis

While the identified modal properties described in the previous section are sufficient to detect the structural degradation based on its influence on the global dynamic response, they fail to provide clear information regarding the location and the extent of damage. A potential indicator for the onset of local damage is nonlinearity in the response. In the following, a nonlinearity indicator (NLI) based on the magnitude-squared coherence function is used to assess nonlinearity in the response between two closely spaced sensors. While usually coherence functions are used to verify linearity between input and output signals, the output signal at a lower floor is treated here as ‘input’ signal for vibrations at a higher floor. The nonlinearity indicator is computed using Eq. 2:

\[
NLI = 1 - \frac{1}{n_{f}} \sum_{i=1}^{n_{f}} C_{xy}(f_{i})
\]  

(2)
In Eq. 2, $C_{xy}$ is the coherence function between signals $x$ and $y$, $f_i$ is the frequency value at which $C_{xy}(f_i)$ is evaluated and $n_f$ is the number of frequency values over which the coherence function is averaged. For an ideal linear system, the coherence function between two signals is equal to unity and thus, the nonlinearity indicator NLI in Eq. 2 equals zero.

The NLI is evaluated for the four damage scenarios described in the previous section (see Fig. 2). The occurrence of nonlinearity is evaluated independently for the west facade (sensor 1 is considered as input and sensor 7 as output) and the north facade (sensor 3 in considered as input and sensor 4 as output) and reported in Fig. 1. The NLI computed for the frequency range between three and eight Hz shows little nonlinearity for the intact building state (less than 2% for the channels measuring in the plane of the walls). With increasing global damage, the acceleration response of the upper floors with respect to the lower floors is increasingly nonlinear. The out-of-plane response of the south wall, in particular, indicates a consistently nonlinear behaviour, which could be an indicator of loss of connection to the floor. A more in-depth analysis is required to assess the fluctuation of the nonlinearity indicator after the onset of damage (from DS 2 to DS 3, a decrease in the nonlinearity is observed for in-plane measurements and the out-of-plane measurement for the west facade). Such a behaviour may be related to elastic nonlinearity [12], or local effects.

The NLI reported in Fig. 4 is calculated over a period of approximatively one minute, when the structure was undergoing vibrations of large amplitudes. In Fig. 5, the influence of the vibration amplitude on the NLI is shown for data windows of a 10 seconds length. All the data-points correspond to DS 1, with little damage. For low-amplitude vibrations, the NLI features a large scatter and tends to high values. This could indicate a low signal-to-noise ratio. Further research is needed to quantify the minimum allowable signal-to-noise ratios to accurately evaluate presence of nonlinearity.
4. CONCLUSIONS

Modelling of existing structures involves many uncertainties. Assumptions based on engineering judgement or guidelines are insufficient to yield reliable estimations. Currently, dynamic measurements do not form part of the seismic assessment, while budget considerations hinder their incorporation into seismic-assessment approaches. Furthermore, confidentiality issues and permanent occupancy prevent deployments in operational buildings. To this end, vibration measurements carried out during a demolition process offer an excellent opportunity to obtain data from real structures under non-conventional loads. The high amplitude excitations and the accumulating damage provide valuable information for identifying damage-sensitive features that are a necessary step towards smart-building applications, such as automated building tagging following seismic events. Furthermore, on an urban scale, the sorting of the stock into structural categories (typologies) facilitates the extrapolation of the findings to buildings of similar features.
This work comprises an effort to explore the potential use of vibrational and video recordings obtained during the demolition of a typical masonry building. The analysis demonstrated the successful application of low cost sensors for the modal identification of the undamaged state. The accumulated damage during demolition could be observed through changes in the modal characteristics. A combined modal index for the robust quantification of the structural degradation was proposed and provided consistent results. In order to increase the “resolution” of the information regarding the localisation and the extent of damage, a nonlinearity indicator based on the coherence function was implemented. The indicator exposed the increased nonlinearity for accumulating damage. Nevertheless, further research is required to assess the fluctuation of the nonlinearity indicator after the onset of damage and to quantify the acceptable signal-to-noise ratios to accurately assess the presence of nonlinearities.

5. ACKNOWLEDGEMENT

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6. REFERENCES


