Integrated structural health assessment of industrial buildings in areas of high seismic risk

Gwenola Michaud[1]*, Roberto Zamparo[1] and Alessandro Brovelli[1] present a study that aims to enhance understanding of structural behaviour under potential seismic loading conditions and to help in maintenance planning of critical infrastructures.

Abstract

In high seismic risk zones, comprehensive structural health assessments are crucial for critical buildings, for example those in the energy distribution networks. Recently, a feasibility analysis was conducted for a pressurised spherical tank for liquified gas storage, demonstrating the validity of structural monitoring using ambient noise. This work presents an extension of the previous work, applied to a different type of industrial building, composed of a steel frame and reinforced concrete. The method was extended, including a pushover analysis to identify critical conditions that may lead to failure. The objective of the work is to identify vulnerable structural components and to predict collapse mechanisms of a structure located in a seismic prone area. The methodology is based on the characterisation of the structure of the shallow subsoil to evaluate the site-specific seismic response and on the identification of the natural resonance modes of the buildings to assess the state of the structure. A combination of passive and active surveys is used to this end. A finite element model is then built and calibrated. Finally, a push-over analysis is carried out to estimate the capacity curve for the structure. Comparison between capacity curves and design spectra would provide insights into displacement demands and elastic behaviour, giving information for enhancing the resilience of the structure and estimating safety thresholds of earthquake intensity, expressed in terms of Peak Ground Acceleration (PGA). Integrating geophysics and engineering knowledge, this feasibility study aims to enhance understanding of structural behaviour under potential seismic loading conditions and to help in after maintenance planning of critical infrastructures.

Introduction

Maintenance of structure and infrastructure systems alongside safety assessment for communities are topical and central aspects of a sustainable territorial management in general, and in high-seismic areas in particular (Cimellaro et al., 2016; Troisi et al., 2021). In seismic-prone regions, the resilience of critical infrastructures requires rigorous structural health assessment and mitigation plans, to ensure prompt reactivations of essential services (e.g. water, electricity and gas distribution) major earthquakes. Recently, a feasibility study was conducted to use an array of tools from the geoscience and civil engineering disciplines to study and monitor the integrity and resilience of a pressurised spherical tank used to store liquified petroleum gas (Brovelli et al., 2024). There are examples of collapsed pressurised spherical vessels during strong earthquakes, and the resulting damages have been extremely severe (Zama et al., 2012; Hatayama, 2015). Building upon the work of Brovelli et al., 2024, an extension of the proposed methodology is presented, applied to an industrial building composed of two sections with very different mechanical characteristics (hence resilience to earthquakes): a steel frame on one side, and reinforced concrete on the other side. The seismic vulnerability of a structure is controlled by its design and the material properties but also on the site characteristics and soil-structure interactions. Any monitoring methodology should therefore consider these three aspects. In addition, in areas with many critical buildings (e.g. refineries, storage sites, chemical factories etc), it is important to be able to perform an initial rapid screening and focus the more detailed investigations only on the structures that have shown higher vulnerability.

This manuscript presents the methodology: from the geophysical characterisation of the near surface up to the push-over analysis to estimate the limit peak ground acceleration that the building under investigation can sustain before undergoing failure. The objective is to provide better characterisation of the structural response, and to facilitate effective risk mitigation strategies (e.g. structural retrofitting), enhancing seismic resilience of essential industrial infrastructures.

Methodology

The methodology for data analysis and modelling includes the following steps:

1. Geophysical characterisation of the soil to estimate the shear wave velocity structure of the near surface and its lateral variability.
2. Ambient noise analyses to assess noise levels, frequency content and data quality during the survey period, as well as their temporal evolution.
3. Power spectral density analysis to identify frequency components which could be associated to modes of the structure.
4. Operational modal analysis (OMA) using a Frequency Domain Decomposition (FDD) algorithm to refine modal estimation.

[1] ISAMGEO

* Corresponding author, E-mail: gwenola.michaud@isamgeo.com

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5. Modelling by finite elements to reproduce natural modes using building design and expected material properties.
6. Push-over analysis to determine the elements of the structure most at risk of collapse of damage during a severe earthquake.

Soil characterisation is performed using multichannel analysis of surface waves (MASW) (Park et al., 1999; Foti et al., 2014) and direction horizontal/vertical spectral ratio (DHVSR) analysis (Havenith, 2004; Chen et al., 2020). The analysis of surface waves using multi-offset acquisition (MASW) is achieved through the deployment of geophones regularly spaced along a line and an active seismic source (seismic hammer) along the same line. The analysis is focused on the propagation of surface waves (Rayleigh waves), particularly on the recording of their vertical component of motion. The propagation velocity of Rayleigh waves is said to be dispersive, i.e. it depends on frequency. Specifically, lower frequencies, and consequently longer wavelengths, penetrate a greater thickness of soil from the surface. Consequently, lower-frequency surface waves, which affect deeper and generally more compact layers, tend to have a higher propagation velocity along the surface compared to higher-frequency waves that affect shallower subsurface layers. The analysis of seismic data in the frequency phase velocity domain provides an estimation of the dispersion curve, from which a 1D S-wave velocity profile can be obtained at the near surface. Repeating the same measurement along different directions and positions within the same site gives also an information about the lateral variability of soil. This is important as in industrial sites the soil conditions often change rapidly as a result of repeated excavations/refilling, hence the geotechnical characteristics can drastically differ from point to point. MASW is an active geophysical method, that can be used in conjunction with passive methodologies, such as (D)HVSR or ReMi (Refraction Microtremor). Focusing on DHVSR, it has the significant advantage that both acquisition and processing are extremely lightweight, and the survey can be quickly repeated on multiple locations, to characterise lateral variability. DHVSR analyses are performed using a single-station, 3-component sensor, which is left on site to record the ambient noise. The ratio between the spectra of the horizonal and vertical components provides information about the subsoil structure and shear wave velocity. The presence of peaks in the H/V spectra can be used to estimate the resonance frequency of the site (Havenith, 2004) while azimuthal variations may provide indications of dipping subsurface layers (Cheng et al., 2020).

The characterisation of the buildings is instead performed using OMA, which is a passive method that relies on ambient noise as the source of energy. In engineering, it is called an Output-Only measure, as the source (input) is not controlled. Using OMA, one can analyse the dynamic response of structures and its temporal evolution, with the underlying assumption that the ambient noise has similar amplitudes and spectral characteristics: in particular it is assumed to be broadband and white (Rainieri and Fabbrocino, 2014). Clearly this is seldom the case, and it is even more unlikely in an industrial context, where the variation of noise levels can be abrupt and content spectral. Due to the presence of engines and other sources of mechanical and electromagnetic noise, the measured spectra are extremely complex to interpret. To partly address this issue, as a part of the proposed methodology it is suggested recording the ambient noise at the base of the building, so that the spurious peaks can be later deconvolved from the measurements. In other words, it is important to be able to discriminate between peaks (in the frequency domain) that are due to the noise itself from the eigenfrequencies of the structure. By using a sensor placed on the soil at the base of the structure, it is therefore possible to study the soil-structure interaction and how the soil vibrations affect the movement of the building.

It is important, when comparing different measurements (in space and or time), to also quantify the noise levels. Due to the stiffness of the structure or the sensitivity of the sensor, certain behaviours may be visible only when the noise level exceeds certain thresholds. To measure the noise level, the Root Mean Squared amplitude (RMS) of each receiver stack is computed on a sliding time window. Each point represents the average noise level at the corresponding time, with higher values indicating stronger seismic or vibration noise while lower values indicate quieter settings. For computation efficiency, following Parseval's theorem, the root mean squared amplitude is calculated in frequency domain.

For OMA, sensors are placed on the structure, possibly near joints and other structural elements. Sensors are typically accelerometers, although our experience has shown that often velocimeters should be preferred, given the higher sensitivity. On the recordings, frequency domain analyses are carried out to assess how the structures respond to dynamic loads or vibrations. This analysis helps in defining the natural frequencies of the structure. This measurement is to be compared with the spectra at the base of the building to identify the peaks that started to appear (or are amplified) in the spectrum, which are likely to be related to the modes of vibration of the structure.

The Frequency Domain Decomposition (FDD) is performed as singular value decomposition on the energy cross-spectra. The resulting singular values are used to refine modes, where peaks can be identified with sufficient accuracy under reduced noise conditions. Each frequency represents a natural frequency of the structure, while the associated mode shape can show how the structure deforms or vibrates at that frequency. For a detailed description of OMA, see Rainieri and Fabbrocino, (2014). The algorithm used for this analysis is documented by Pasca et al. (2020).

The structural elements for the finite element modelling of the building structure are represented as one-dimensional elements for beams and columns, and two-dimensional plate elements for the reinforced concrete wall. The type of structure and its behaviour are defined by its floor load geometry and its characteristics. The wall infills are included by defining linear loads applied to the beams.

Once the most representative model is created, a nonlinear push-over analysis is conducted to estimate failure mechanisms and thresholds. The goal is to correlate the push-over analysis with the maximum displacements that building elements can sustain, and relate it to a measure of earthquake intensity, such as Peak Ground Acceleration (PGA). In this way, the operator of the site or building can set up appropriate responses to take in case a seismic event exceeds the PGA limit. For the push-over analysis, taking response spectra from a regional database, the intersection of a radial line on the elastic portion of the capacity curve with the design spectrum provides estimation of the displacement demand (Fajfar, 2021). In this way, modelling can be done to determine if displacements remain within the elastic range or exceed it, still satisfying the displacement demand without reaching collapse.

Data acquisition summary

- Data acquisition is organised in phases following survey design as shown in Figure 1.
- Multichannel analysis of surface wave data, with 2 perpendicular acquisition lines following the directions of the structures.
- Site and structure survey to collect the necessary information for model construction, with position and geometry of key structural elements.
- Passive monitoring of the structure with one velocimeter deployed near the building and 3 to 6 accelerometers installed on the walls/structural elements of the building for at least a few days and up to one week. The accelerometers can be installed on the reinforced-concrete walls or the steel pillars. This is quite different from what is typically done in traditional modal analysis, where data acquisition lasts from a few (15) minutes to a few (2-3) hours. Acquisition of longer time-series does not increase the installation costs and allows us to (1) improve the signal to noise ratio through data staking and (2) select appropriate time windows for signal extraction. Ultimately, a longer time series makes the processing robust and reliable. This is particularly important as changes in eigenfrequencies can be subtle.

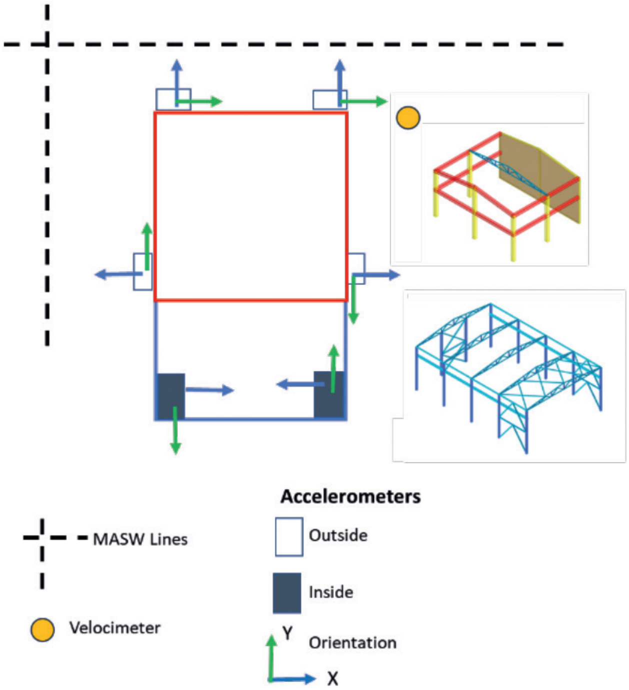


Figure 1 Example of data acquisition geometry for a rectangular cuboid structure composed of steel frame and reinforced concrete part.

Data analysis

The analysis of the surface wave data as MASW gives a velocity profile for S-waves from the picking and the inversion of the dispersion curves of phase velocity versus frequency (Figure 2). This profile provides information on the very near surface up to 20-30 m, and characterises the near-surface condition where the structures are. The Vs30 profile, i.e. shear velocity profile in the top 30 m is a typical proxy for geotechnical characteristics.

The ambient noise analyses are done on each receiver, being accelerometer or velocimeter with the objective to quality-control each instrument and the data completeness during the data acquisition. In Figure 3, the root mean squared of each receiver stack is computed on a sliding time window of 30 min, every 15 min for the entire data acquisition period. The ambient noise varies as a function of activity change on site. For instance, days and nights are well marked, with a constant minimum amplitude floor for the entire survey. In addition, the morning and afternoon time frames are also consistent. Finally, smaller operational noise is observed during Sundays with fewer activities compared to the rest of the week.

The analysis in the frequency domain is made on each component of the accelerometers deployed on the reinforced-concrete walls or steel pillars of the structure (Figure 4). Some peaks of frequency are visible around 2 Hz, 5 Hz, between 6 and 7 Hz as well as around 8 Hz, 9 Hz and 10 Hz. The largest amplitudes on the power spectral density are usually on the inside accelerometers, installed on the steel frame and on the

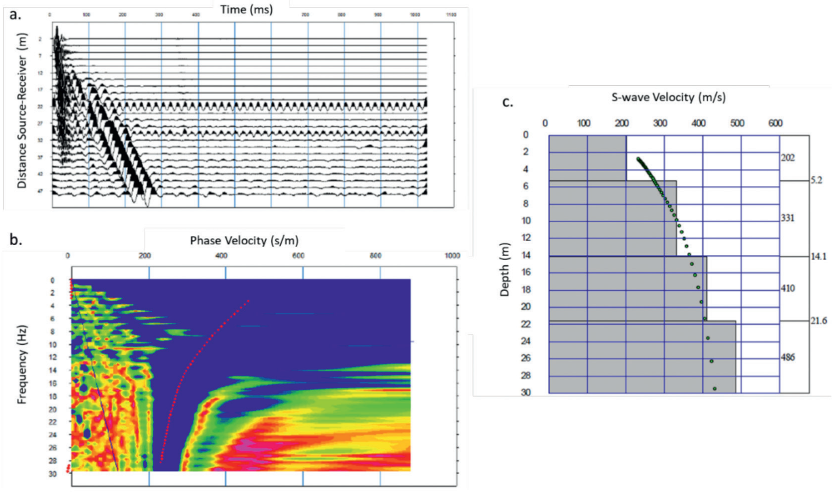


Figure 2 Illustration of MASW analysis on shot gather (a), with dispersion curve picking on phase velocity versus frequency plot (b) and its inversion to obtain S-wave velocity profile (c).

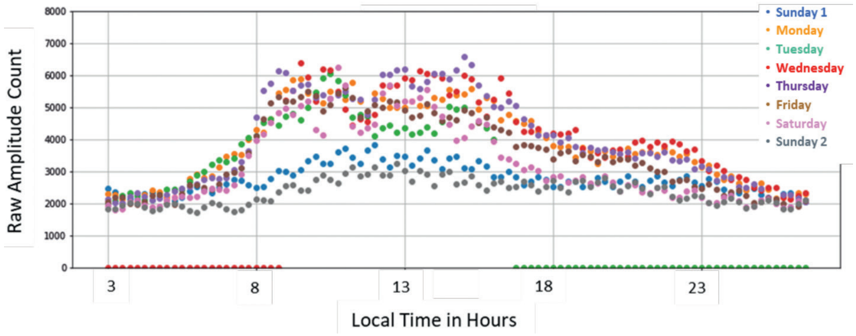


Figure 3 Example of ambient noise analysis as RMS values estimated over a sliding time window of 30 min, every 15 min.

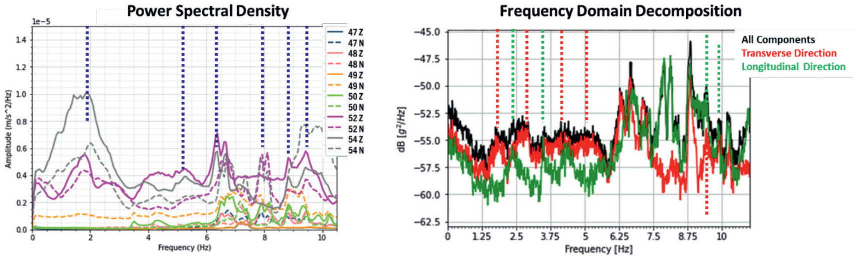
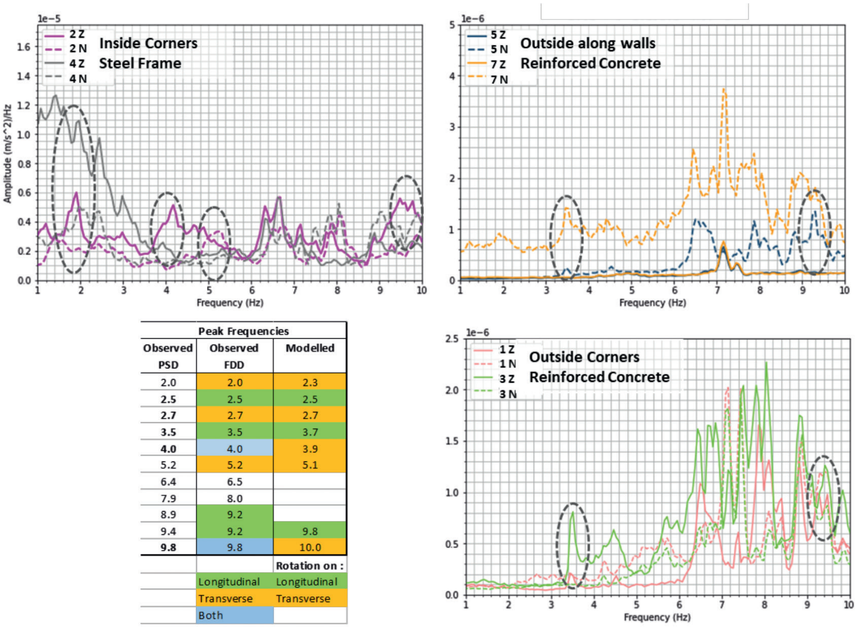


Figure 4 Frequency Domain Analysis on each component (left) and Frequency Domain Decomposition (right).



Peak Frequencies		
Observed PSD	Observed FDD	Modelled
2.0	🟧 2.0	🟧 2.3
2.5	🟩 2.5	🟩 2.5
2.7	🟧 2.7	🟧 2.7
3.5	🟩 3.5	🟩 3.7
4.0	🟦 4.0	🟧 3.9
5.2	🟧 5.2	🟧 5.1
6.4	6.5	
7.9	8.0	
8.9	🟩 9.2	
9.4	🟩 9.2	🟩 9.8
9.8	🟦 9.8	🟧 10.0
		Rotation on :
	🟩 Longitudinal	🟩 Longitudinal
	🟧 Transverse	🟧 Transverse
	🟦 Both	

Figure 5 Comparison between observed peak of frequencies in PSD and FDD (bottom left) and power spectral density as a function of receiver positions inside the building on steel frame (top left), outside along walls (top right) and at outside corners (bottom right).

component perpendicular to the structure in grey and pink solid lines on Figure 4 (left side).

These peaks are also visible on the FDD results obtained considering all the accelerometers at once. On Figure 4 (right side) are plotted the 1st single value for 3 cases, considering:

- All components regardless their directions in black,
- The components along the transverse direction of the building in red,
- The components along the longitudinal direction of the building in green.

The frequency domain decomposition provides a way to ease and refine the identification of the potential natural modes. For instance, the largest peaks observed on the power spectral density around 2 Hz are not any more the largest on the frequency domain decomposition (Figure 4). Instead, the largest peaks are around 7 Hz, 8 Hz and 9 Hz. In addition, it is easier to visualise the potential natural modes on the frequency domain decomposition: all peaks observed on the power spectral density can be seen on the frequency domain decomposition, but are seen on the frequency domain decomposition more clearly. The peak of frequencies obtained by the frequency domain decomposition can be seen on the power spectral density displayed as a function of receiver positions (Figure 5).

For the frequency domain decomposition, comparing the result obtained with all components versus with separate directions, i.e. longitudinal or transverse directions of the building, the provided curve with all components is the envelop of the curves obtained for the 2 distinct directions of the building (Figure 4). Considering components laying on the same direction eases the comparison with the modelling results given as a function of the structure directions. The outside receivers, deployed on the reinforced concrete present similar spectrograms with respect to the inside receivers, deployed on the steel frame. The building vibrates differently as a function of the composition and geometry of the structure parts.

Finite element models and pushover analysis

The modelling of a building begins with the structural design and an onsite survey to understand the main elements of the building, including their dimensions, geometry, properties, and connections. This step is crucial for assessing the rigidity and strength of the various structural elements. In the finite element method (FEM), structural elements such as beams and columns are modelled with one-dimensional elements, while walls are modelled with two-dimensional elements. For this project, most common materials were assumed based on European standards for steel and concrete.

From Earthquake Hazard Map, lateral elastic design spectra are estimated for various types of earthquakes. These spectra are functions of ground motion levels, the probability of exceedance within 50 years, and the corresponding return periods (Table 1).

For each type of earthquake, a displacement shape is assumed, and the vertical distribution of lateral forces is determined for the structure. The relationship between base shear and top displacement is then defined, using displacement of a representative control node, typically located at the centroid position of the roof. After this estimation, the bilinear capacity curve is plotted against the design spectra for this location (Figure 6). At the end, the Peak Ground Acceleration (PGA) for the building is estimated as 40% of the scaled elastic design spectrum plateau.

The push-over analysis was conducted for the building, considering its distinct structure parts: the inside steel frame and the outside reinforced concrete behind a shear wall (Figure 7). These two parts are structurally independent of each other, without any rigid connections between them. For the steel part, it was not necessary to scale the spectrum to find the PGA for the transition from the elastic to plastic field, as the capacity curve is well above the design spectrum, even in the worst case scenario of a DD-1 type of earthquake (Figure 7 Top). This part of the structure is expected to remain largely intact, even under the largest possible seismic event. However, damage to secondary parts and infill walls can still be expected.

Earthquake Type	Probability of Exceedance within 50 Years	Return Period
DD1	2%	2475 years
DD2	10%	475 years
DD3	50%	72 years

Table 1 DD1, DD2 and DD3 earthquake types.

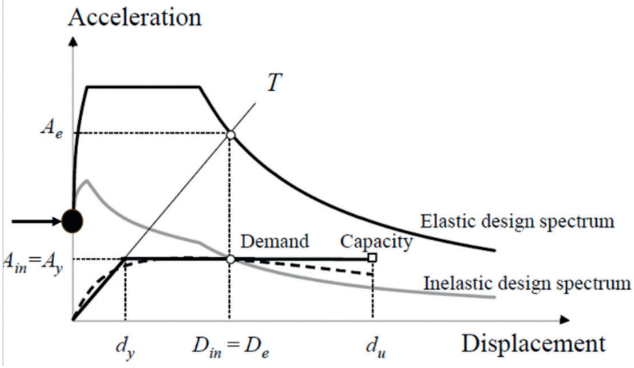


Figure 6 Design spectrum and capacity curves with indication of how PGA is estimated as 40% of design spectrum plateau (From Fajfar, 2021).

For the reinforced concrete part, after scaling the design spectrum for a DD-1 type scenario, its plateau is estimated at a value of 1.40 g. The PGA, calculated by considering 40% of this value, results in 0.56 g.

Discussion

During this analysis, frequency domain decomposition was key to refining the individual peaks observed on the power spectral density. Generally, frequency domain decomposition presents clearer peaks in terms of amplitude and shape than those observed in the power spectral density. Exploring the frequency domain decomposition using components pointing in the same direction helps to refine data comparison and analysis. Additionally, decomposing the frequency domain into longitudinal and transverse directions eases the comparison with the finite-element modelling results, provided along those directions.

During this study, the focus was on the identification of the natural modes. The analysis can be further expanded also considering modal shapes. These give additional insights into the dynamic behaviour of the buildings, in particular its intrinsic damping, to better understand how the structure deforms or vibrations at those frequencies.

Conclusion

This paper presents the application of a monitoring method to assess the structural health of mission-critical industrial buildings in high seismic risk zones. This study is based on a methodology for comprehensive assessment, combining geophysical and engineering knowledge to broadly understand how a given structure on a specific site can sustain major earthquake.

Through a combination of passive and active surveys, the study effectively characterises the shallow subsoil and identifies natural resonance modes of the building. It provides insights into the structural integrity and potential vulnerabilities for a given building at a specific site. This work is a groundwork for informed maintenance planning and risk mitigation strategies to enhance the resilience of critical infrastructures and to ensure their continued functionality and safety in the face of natural hazards.

The thresholds of potential damage during a major earthquake are key to planning a structural health monitoring system for potential post-event evaluation. In particular, the plateau values can be compared with the measured values on building elements during earthquakes and the present natural modes with post-event modes.

In the data analysis, the identification of the frequency and mode peaks was seen as crucial to calibrate the model. Model calibration may require adjusting material properties and checking element geometry and properties. In this analysis, the comparison between observations and modelling was good, validating the monitoring method application in structural health assessment for such buildings and sites.

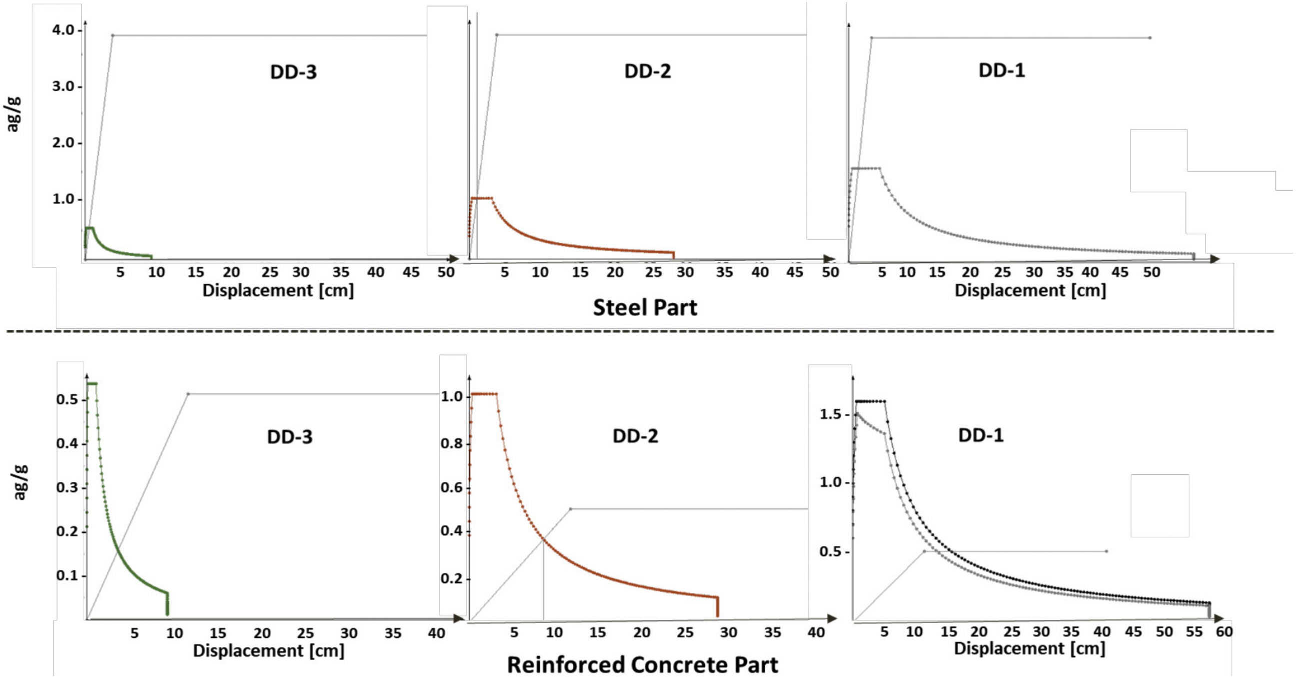


Figure 7 Lateral Elastic Design curves for DD-3 in green, DD-2 in red, and DD-1 in grey, along with the bilinear curves for the metal part of the building (top) and reinforced-concrete part (bottom).

For future projects, it would be interesting to apply this monitoring method to tall structures and to assess how the structural health evaluation varies as a function of receiver coverage following recently published work such as Aytulun and Soyoz (2023).

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