Reducing the uncertainty on the structural behaviour of existing structures through data interpretation

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Abstract

This paper presents a methodology for reducing the uncertainty related to the structural behaviour of an existing building in view of a vulnerability assessment regarding future earthquake actions. Estimating the lateral load resistance is a step towards evaluating the capacity of a structure to resist earthquake actions. The prediction of structural behaviour by numerical models is inevitably biased, and the importance and correlation of those modelling errors is unknown. In addition, due to the lack of knowledge on the uncertainties related to existing structures, more than one model may explain the observed behaviour. Consequently, a data-interpretation methodology that is robust in the presence of errors of unknown spatial correlation is applied to separate candidate models from unlikely ones. The first natural frequency derived from ambient vibration measurements is proposed to falsify those model instances that are inconsistent with the monitored behaviour.
The identified candidate models are used to predict the lateral load resistance of a mixed concrete and masonry building studied for illustration. The number of model instances and the parameter uncertainties could be substantially reduced by interpreting ambient vibration data, showing the potential of the proposed methodology. Nevertheless, no significant reduction in the prediction range could be obtained and future work is needed to allow a meaningful assessment of the structural vulnerability.

1. Introduction

Predicting the structural behaviour of existing buildings using measurements is a challenging inverse engineering task. The size of full-scale engineering structures further increases the complexity related to estimating the load bearing capacity of existing buildings. However, retrofitting and replacement of existing buildings is economically and environmentally demanding. Therefore, techniques that reduce uncertainties related to the load-bearing behaviour of existing buildings are of interest.
An important aspect when predicting the behaviour of existing buildings concerns the epistemic uncertainties that are introduced by the use of simplistic models, such as the ones often used in the design stage. There is potential to reduce model-related uncertainties by interpreting the data of ambient vibration measurements of the building (Michel et al., 2012). Liel et al. (2009) discussed the importance of taking uncertainties into account, stating that neglecting them is likely to produce predictions which are not conservative. Uncertainties related to parameter values can be reduced through model updating from ambient vibrations (Jaishi and Ren, 2005).
Some authors proposed model updating based on ambient vibrations to predict the vulnerability of structures against future earthquake actions (D'Ambrisi et al., 2012; Foti et al., 2012). However, the finite-element models that are used are tuned in order to reproduce the measured dynamic behaviour as closely as possible. In general, the validity of predictions made by such calibrated models is limited to the calibration data domain. Diagnostic tasks are inherently ambiguous even without considering uncertainties. Since structural identification has to account for measurement and modelling errors, it is very likely that many models are able to explain the measured behaviour. Furthermore, for complex

engineering structures, systematic uncertainties that are spatially correlated undermine efforts to idealize modelling errors as independent random variables.
To overcome these shortcomings, Goulet and Smith (2013) proposed a probabilistic model falsification framework based on populations of models. This methodology has been successfully applied to diagnosis of structures where uncertainty cannot be entirely defined. In addition, prognosis of fatigue lives has shown the potential of the methodology (Pasquier et al., 2014). However, this technique has never been used to estimate ultimate load bearing capacity.
This paper presents a methodology that reduces the uncertainty related to the behaviour of structures by using natural frequencies derived from ambient vibration measurements. Model falsification is applied to discard model instances that fail to predict the first natural frequency of the building. The population of models that cannot be falsified is used to predict the lateral force resistance of a building.
The next section exposes the methodology of model falsification and prediction of the lateral load resistance. The results of data interpretation are used in the following section to estimate the lateral load resistance of a mixed concrete and masonry building tested on a shaking table.

2. Multiple-model data-interpretation methodology

2.1 Error-domain model falsification

Model-based system identification, defined as the specific task of inferring parameter values of physical models from measurements (Ljung, 2010), is an inverse engineering task. Consequently more than a single model explains the behaviour of a structure that is observed for given conditions (Raphael and Smith, 1998). This concept has been adapted to probability-based diagnosis of structures by Goulet et al. (2010).
The error-domain model falsification methodology is based on the concept of falsifying models that fail to explain the measured behaviour, rather than validating or optimizing models to give the best match with the measurement data. Uncertainties and errors are estimated in order to define criteria to reject unlikely models. All remaining models are called candidate models and they are treated as equally probable.
The starting point of the methodology is the definition of bounds on parameter values and errors. There are not only measurement errors, for which independent zero-mean Gaussian distributions can be reasonably assumed. When building a numerical model, regardless of sofistication, inevitable omissions and simplifications are introduced that result in unknown spatially corellated errors. The error-domain model falsification methodology overcomes the shortcomings of current methodologies regarding the unknown probability density functions of epistemic errors (Goulet and Smith, 2013).
The structure is represented by a physics-based behaviour model g(.), that describes one possible model class among others. This model g(.) is based on a set of n_p physical input parameters $\boldsymbol{\theta}$, that cover the domains of realistic values for geometrical and material properties of the structure as well as for the boundary conditions.
The prediction of the model g(.) with the right parameter values $\boldsymbol{\theta^*}$ would equal the *'real value'* of the structure plus the modelling error related to the assumptions inherent in the model class g(.). Similarly, a measured value y_i gives the *'real value'* contaminated by an unknown measurement error. Hence, we find the general equality that allows to compare model predictions to measured quantities (Eq.1).

$$g_i(\boldsymbol{\theta}) - \epsilon^*_{model,i} = y_i - \epsilon^*_{measure,i} \qquad)$$

Although, neither the real value, nor the measurement and modelling errors can be known or determined, engineering heuristics provide good estimates of the bounds to the measurement and modelling uncertainties. Based on the estimation and the combination of the different sources of uncertainties, a random variable describing the residual can be computed between the predicted value $g_i(\boldsymbol{\theta})$ and the measured value y_i. Based on this random variable, thresholds $[T_{low,i};T_{high,i}]$ on the residual can be defined yielding a given target probability.
Consequently, a model is falsified if it fails to meet Eq. 2 for every measurement *i*.

$$\forall i \in \{1, \dots, n_{m\}}: T_{low,i} \leq g_i(\theta) - y_i \leq T_{high,i} \qquad 2)$$

The whole model class is falsified when no model instance satisfies Eq. 2, indicating that wrong assumptions were made in process of building the model. This capacity of rejecting whole model classes is an important asset of the error-domain model falsification methodology, providing a robust prognosis.
The candidate model set is composed of the models that have not been falsified. All instances from the candidate model set are treated as equally probable. Thus the subsequent prediction of the lateral load resistance is done on the population of candidate models.

2.2 Lateral load-bearing capacity estimation

The candidate models that are identified through the error-domain model falsification are used for the static prediction of the normal force acting on each wall of the ground floor. The normal force is a main parameter in the subsequent prediction of the lateral load resistance of each wall that is parallel to the direction of motion.
The simplified model of the Eurocode 8 (EN1998) is used to predict the lateral load resistance of the masonry walls. This model predicts the load resistance for two different failure modes – rocking and shear. The given formulas are very similar to the ones proposed by Magenes and Calvi (1997) for walls with fixed boundary conditions. Nonetheless, there can only be an approximation of the maximum base shear, due to the lack of experimental data near collapse for shear wall structural systems and the heavy inherent simplifications.
The resistance of the wall against a rocking failure, given by Eq. 3., is calculated by taking into account the compressive strength of the masonry f_x in the crushing toe of the wall.

$$V_{Rd,R} = \frac{l_w \cdot N_x}{2 \cdot h_w} \cdot \left(1 - 1.15 \cdot \frac{N_x}{l_w \cdot t_w \cdot f_x}\right) \qquad (3)$$

Besides the known geometric parameters of a single wall, namely the length l_w, the height h_w and the thickness t_w, the normal compressive force N_x acting on the wall is the most important parameter.
Eq. 4. determines the resistance to shear and includes consideration of the part of the wall that is in compression.

$$V_{Rd,S} = \left(1.5 \cdot \frac{f_{v0}}{0.85 \cdot f_x} + 0.4\right) \cdot N_x \qquad (4)$$

Similarly to Eq. 4., f_x is the compressive strength and f_{v0} is the shear strength of masonry without a compressive force. Finally, the shear resistance of the masonry walls is given by the minimum of the lateral load resistance against rocking and shear respectively.
Contrary to the masonry walls, the concrete wall is considered to be continuous over the total height of the building. Hence, it is most vulnerable to a flexural failure mode. By supposing a triangular distribution of the lateral forces, the lateral load resistance can be estimated to be the resisting flexural moment of the base section divided by two thirds of the total height of the building. The resisting moment of a reinforced concrete section is determined by the well-established analysis method of reinforced concrete by assuming the hypothesis of an equivalent stress block for concrete.

3. Case study – Mixed masonry and concrete building tested on a shaking table

3.1 Shaking table test description

The case study described in this paper consists in a half-scale four-storey building with reinforced concrete and unreinforced masonry walls (Beyer et al., 2014). The building has been tested on a shake table at the laboratory of the European Centre for Training and Research in Earthquake Engineering and Seismology (EUCENTRE TREES) and the results have been made accessible (Tondelli et al., 2014).
The structure has been subjected to multiple test runs. The test runs were characterized by increasing intensities going from 0.05 g for the first test run to 0.9 g for the last. The varying intensities covered structural-performance states from minor deterioration to near collapse. From these tests, the force-displacement behaviour of the building has been inferred.
Between two consecutive test-runs, low-amplitude white-noise accelerations were applied to the building in order to simulate ambient vibration monitoring. The ambient vibration recordings made prior to the first test run were used for the structural identification of the undamaged building described in this paper.
In order to determine the natural frequencies of the building, the power spectral density (PSD) is computed based on a Fourier transform of the acceleration data. The first longitudinal frequency is found to be around 7.4 Hz, as it presents the highest peak in the PSD range below 10 Hz. Figure 1 shows the PSD and the peak at 7.4 Hz derived from the acceleration time series recorded at the 4th floor. Further information on the shaking table tests is provided by Tondelli et al. (2013).

3.2 Numerical model

A finite element model of the structure has been constructed to predict the natural frequencies of the building. The structural components have been modelled using solid elements with a linear elastic behaviour model. The finite element model and the principal geometric characteristics of the building can be seen in Figure 2.
The laboratory structure is at half-scale, thus unreinforced concrete blocks were placed on the four slabs in order to keep stresses induced by gravitation equal to the full-scale value. Since these blocks were to act as supplementary weight without increasing the stiffness of the slabs, plastic sheets were placed between the blocks and the slab. The contribution of the additional concrete blocks to the slab stiffness is still uncertain, therefore the horizontal connection between the blocks and the slab has been modeled by translational springs. The behaviour of the connection changes from free movement to fixed conditions between 0.1 N/mm and 100 N/mm.

While the concrete walls and their reinforcement can be treated as continuous from the base to the top of the building, the masonry walls are interrupted at every floor by the concrete slab. Given the uncertainty about the mortar layer between masonry blocks and the concrete slab, this connection has also been modelled by a horizontal spring of a stiffness between 0.1kN/mm and 100 kN/m.
The uncertain material properties for the analyses of the dynamic properties of the building are the Young's moduli and the densities of concrete and masonry respectively. Additionally, there was significant uncertainty on the stiffness values for the simulated springs between the masonry walls and concrete slabs and between concrete blocks and concrete slabs.
Three other parameters are introduced for the prediction of the lateral load resistance; the compressive strengths of masonry (f_x) and concrete, and the yield strength of the reinforcement bars. An overview of the parameters and their ranges is given in Table 1.
The effect of the respective Poisson's ratios of concrete and masonry as well as the out-of-plane stiffness of the masonry walls perpendicular to the direction of motion was determined to be insignificant within the context of solving for natural frequencies. Consequently they were omitted from the set of primary parameters.

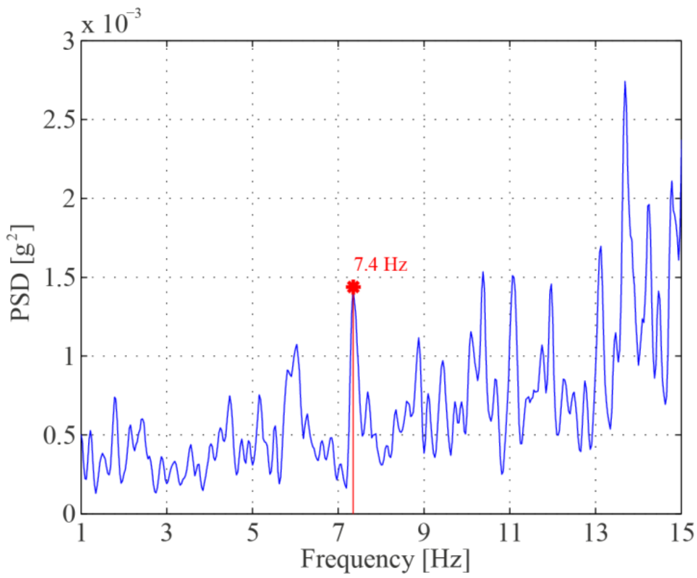

Figure 1: Power spectral density estimation for the longitudinal signal recorded on the upper floor

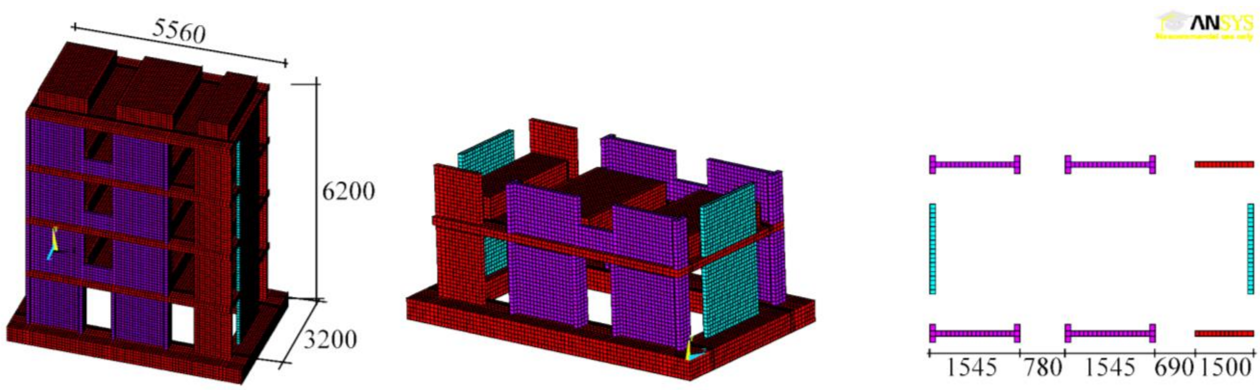

Figure 2: Numerical model and principal geometric characteristics of the building

3.3 Model falsification

Model falsification has been performed based on the first longitudinal frequency. Figure 3 shows the frequency prediction based on the model population resulting from all possible combinations of six first parameter values (cf. Table 1). As the material strength does not influence the elastic frequency they were omitted from Figure 3 for a better visualization.
Thresholds are defined in order to falsify the models that fail to give frequency predictions compatible to the measurements (cf. Eq. 2). The frequency thresholds are defined by combining the uncertainty sources that were identified through a Monte-Carlo scheme. Three additional sources of uncertainty have been assumed.
Uncertainty in the acceleration measurement and recording is estimated to be a zero-mean Gaussian distribution with a standard deviation of 2.5%.
The frequency determination from the acceleration time-series requires Fourier transforms and visual interpretation of the power spectral densities, producing an estimated error of up to ±2%.
The finite element model introduces simplifications, assumptions and omissions. For example springs were used to model the contact behaviour between elements. In addition, solid elements tend to overestimate the stiffness in comparison with plane elements. Therefore, the frequency prediction resulting from the model is evaluated to have an asymmetric error, comprised between an upper bound error of 10% (correction of -10%) and a lower bound error of 5% (correction of +5%). Table 2 summarizes the uncertainty sources that were used in the analysis.
The frequency of 7.4 Hz that was derived from measurements resulted in 246 of the initial 288 model instances to be falsified. This corresponds to a reduction in the model population of 85%. Figure 3 shows the candidate models and the falsified models alongside the thresholds derived from the distribution of the combined uncertainties.
As can be seen in Figure 4 (on the left), the parameter ranges could only be reduced for the connection parameters and not for the remaining parameters. This phenomenon can partially be explained by the relative importance plot for the different parameters (Figure 4 on the right) that underlines the important influence of connection stiffness on frequency prediction.

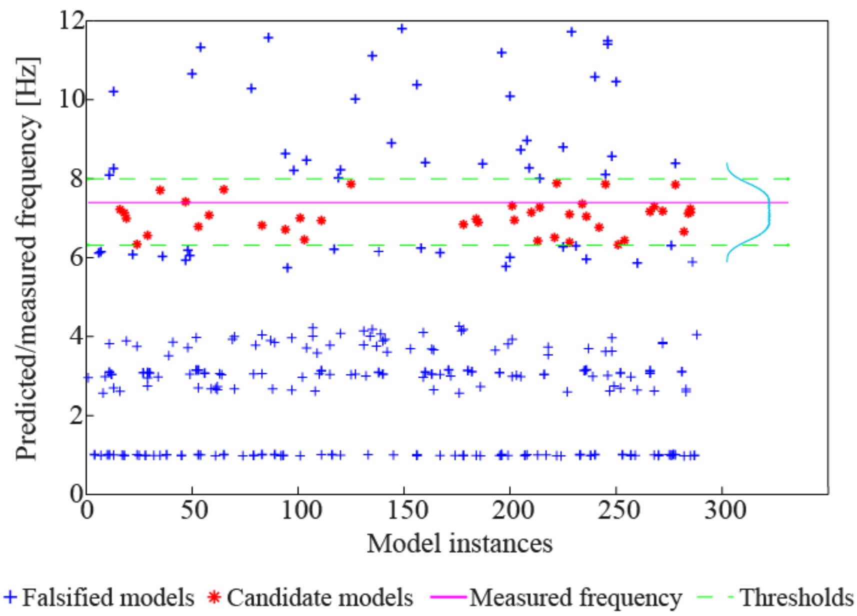

Figure 3: Candidate model selection based on combination of uncertainties

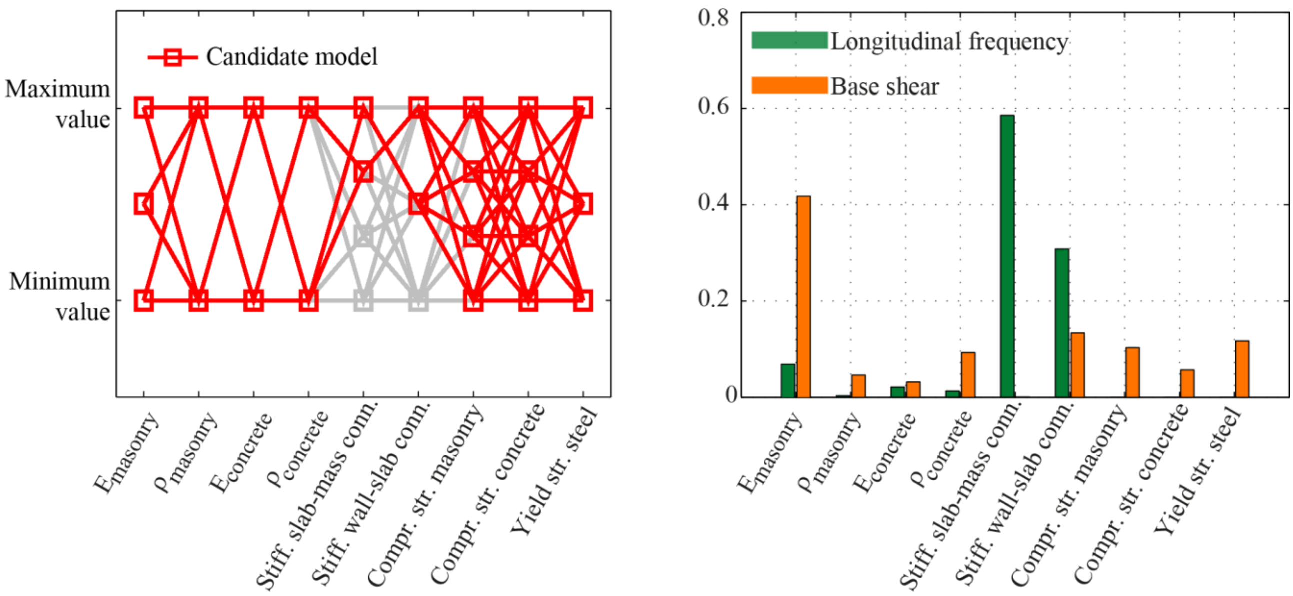

Figure 4: Normalized parameter combinations of the candidate models (on the left) and relative importance of each parameter on the prediction of frequency and base shear (on the right)

Table 1: Selected parameters and their respective ranges

Parameter	Units	Minimum	Maximum	Divisions
Young's modulus for masonry	GPa	4	12	3
Density for masonry	t/m3	1.0	1.3	2
Young's modulus for concrete	GPa	27	33	2
Density for concrete	t/m3	2.4	2.5	2
Connection stiffness for supplementary masses	N/mm	0.1	100	4
Connection stiffness between masonry walls and concrete slabs	kN/mm	0.1	100	3
Compressive strength of masonry	MPa	7	16	4
Compressive strength of concrete	MPa	28	36	4
Yield strength of reinforcement bars	MPa	500	560	3

Table 2: Identified sources of uncertainty and their probability distribution

Uncertainty source	Units	PDF	Minimum	Maximum
Poisson's ratio of concrete	-	UNIF	0.1	0.25
Poisson's ratio of masonry	-	UNIF	0.1	0.3
Young's modulus of masonry loaded out of plane	GPa	UNIF	3	10
Measurement uncertainty	%	NORMAL	0 (mean)	2.5 (st.dev.)
Frequency determination uncertainty	%	UNIF	-2	2
Model error	%	UNIF	-10	5

3.4 Lateral load resistance prediction

The maximum base shear of the studied building has been evaluated for the initial model population (13824 model instances) and for the candidate models (2016 model instances). Although there is a large reduction in the number of models, the range of predicted lateral load resistance for the candidate models (280-360 kN) is only slightly less than that of the initial model population (280-370 kN). The distribution of the predictions prior to and after the falsification are shown in Figure 5. The primary reason for the lack of reduction in the prediction range originates from the material stiffnesses, material strengths, and assumed wall-to-slab connection stiffness. With exception of the connection stiffness, the ranges of these parameters could not be reduced in the falsification process, due to the relatively low importance (cf. Figure 4 on the right).
Thus, it can be concluded that natural frequencies derived from ambient vibration monitoring may be unsufficient to obtain an effective reduction in the prediction range of lateral load resistance.
It has to be noted that compared to the base shear that has been measured during the shaking table tests (a maximum of 600 kN has been derived from the measurements), all the predictions remain very conservative.

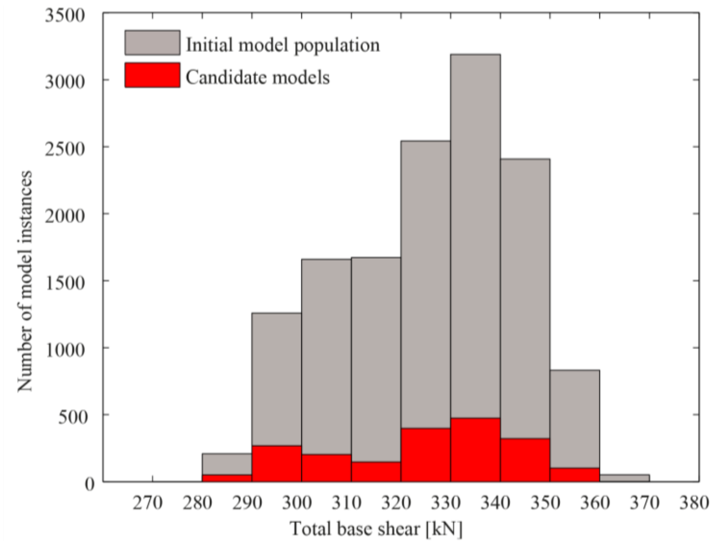

Figure 5: Distribution of the lateral load-resistance prediction for the initial model population and the identified candidate models

4. Conclusion

This paper presents the application of a model-falsification approach to the prediction of the lateral-load resistance of a building. The methodology is applied to a mixed concrete and masonry building. By interpreting natural frequencies derived from ambient vibration measurements, the following conclusions could be drawn:

- The number of model instances could be reduced by 86% by applying model falsification based on the first natural frequency.
- The uncertainty related to the contact between different structural elements could be significantly reduced.
- Natural frequencies derived from ambient vibrations alone may be unsufficient to improve lateral-load-resistance predictions.

Future work is needed to a better vulnerability prognosis. Use of the predicted lateral load resistance and stiffness of the building as a starting point to perform a non-linear analysis (e.g. by applying a Takeda behaviour model) may be useful. A nonlinear structural analysis provides an estimation of the force-displacement behaviour for the building, and consequently the vulnerability with respect to various earthquake intensities can be derived.

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