

SEISMIC HAZARD ASSESSMENT OF HISTORIC RESIDENTIAL BUILDINGS UTILIZING IN-SITU MEASUREMENTS

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Abstract. *In this paper a simple and economically competitive procedure for the seismic assessment of historic buildings is proposed. The approach is based on a combination of experimental investigation with successive numerical analysis. The dynamic parameters of the building such as natural frequencies and mode shapes are determined from in-situ measurements. A simplified mechanical model, where the mass is lumped to the story levels, represents the building. The distributed stiffness of the model is identified by a finite element modal update procedure utilizing the experimentally determined characteristics. A pushover analysis yields the capacity curve, and a capacity spectrum is utilized to determine the performance point. Consequently, the seismic vulnerability of the original object can be evaluated. Structural changes (mass, stiffness) of projected reconstructions are considered in a modification of the mechanical model, and seismic assessment is performed as for the original structure.*

1 INTRODUCTION

In the urban areas of Central Europe a noticeable amount of residential buildings are older than 90 years. For instance in the city center of the Austrian capital Vienna approximately 32.000 houses were erected between 1850 and 1918, which is about one third of the present-day stock of buildings. Mostly, these structures have been retained unchanged without considerable structural improvement since decades. Many of these objects are landmarked, and space is limited for the construction of new houses, and thus, in the last twenty years unused attics of these historic buildings were converted into new apartments in order to recreate additional living space.

The reconstruction and development of attics in historic buildings is regulated in national standards [1]. Since recent investigations have revealed that in Central Europe the earthquake hazard was underestimated considerably, these regulations were tightened in spring 2006 by increasing the effective earthquake loads. In [1] for the assessment of sufficient seismic resistance of existing buildings the following cases are distinguished:

- Up to an additional vertical load of 7.2 kN/m^2 a simplified seismic analysis is permitted.
- For larger additional loads sophisticated seismic analysis procedures must be applied.

The simplified analysis is applicable only for lightweight constructions with a small increase of vertical loads. However, in the vast majority of cases the earthquake resistance of the structure to be remodeled must be verified by means of complex numerical methods considering large uncertainties, and the expenses for most reconstructions increase dramatically. The actual condition of the masonry of old buildings is in general hardly known, and the structural system and parameters are in general not well documented. There is also a lack of information on parameters of construction material utilized in ancient houses. It is a matter of fact that the new regulations led to a major decline of reconstruction of historic buildings and thus, to economic disadvantages for the real estate market.

Hence, there exists a high demand for an economic and sufficient accurate seismic analysis, which is relatively easy to implement. In this paper a simplified method based on combined experimental – numerical analysis is presented.

2 METHODOLOGY

2.1 In-situ measurements

Seismic analyses are based on basic dynamic parameters of the considered object such as natural frequencies and the corresponding mode shapes. For existing buildings these parameters are determined beneficially from data recorded by in-situ measurements, in particular when structural system and utilized materials are unknown. It is proposed to utilize accelerometers, which are distributed on the story levels on top of each other. As an example Figure 1 shows the position of accelerometers in an actual investigated residential building in Vienna. The sensors are placed next to the staircase because the apartments are occupied, and thus cannot be entered without additional logistic effort. Advantageously, the measurements are performed during the night when foot traffic is low and excitation from engines such as washing machines is very unlikely.

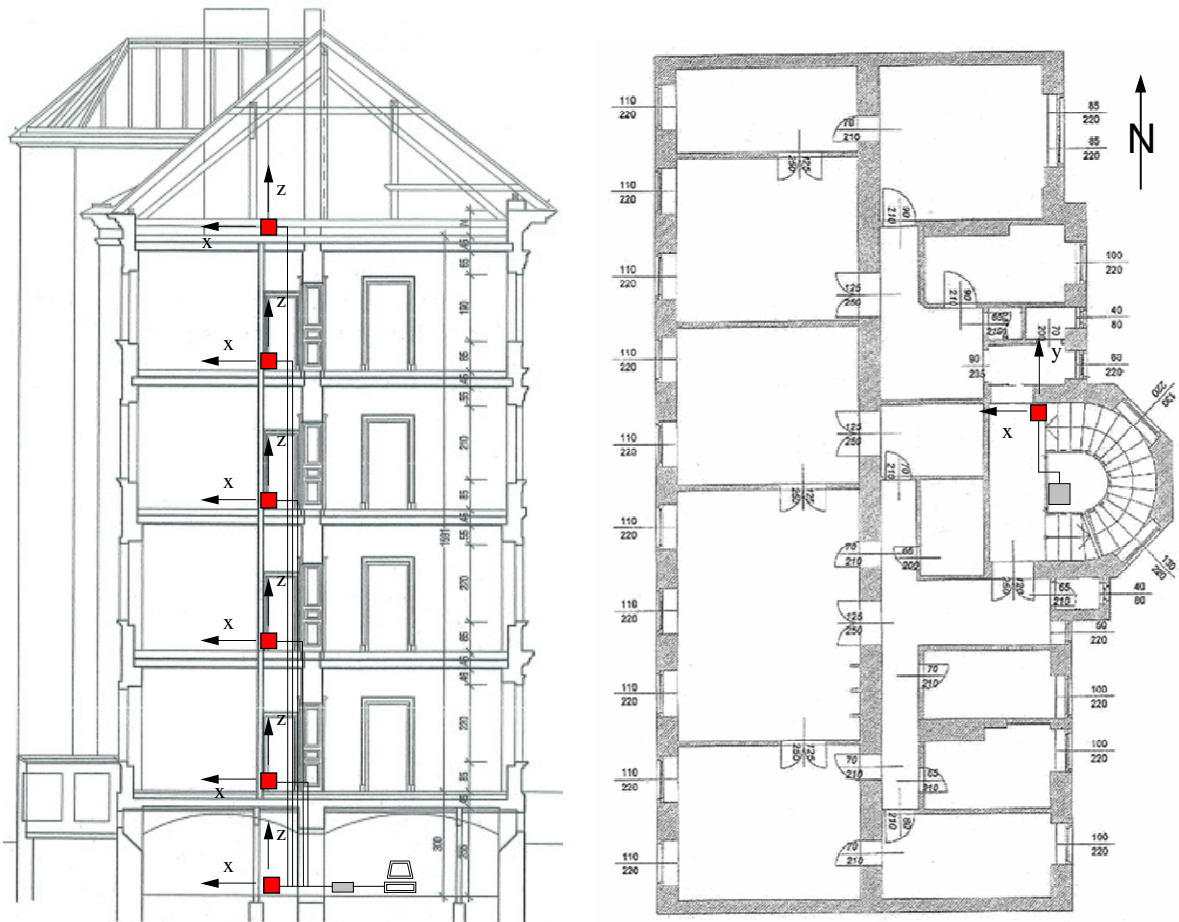


Figure 1: Sensor instrumentation of a residential building

In tall buildings measurements cannot be conducted simultaneously, because the number of available sensors is customarily limited. For such objects a reference sensor is located in a story, where it remains during the entire measurement period. After each measurement a second accelerometer is moved to a further measuring point at a different story level until the entire building is surveyed. The response of the sensor to be moved is related to the response measured with the reference sensor.

Depending on the type of building and measurement equipment two different analysis techniques based on:

- the ambient vibrations response (ambient excitation)
- the free vibration response after an impulsive like load applied with a hammer (transient excitation)

may be utilized to evaluate the dynamic parameters.

It is noted that the location of excitation must remain the same when measurements are performed with a reference sensor.

2.2 Signal processing

The dynamic time history response is recorded in three directions. However, if reasonable the evaluation of the data is confined to one building axis, where the structure is most vulnerable, i.e. effects such as torsion or coupled bending torsional vibrations are negligible.

The natural frequencies of the building structure are determined by transforming the time-history signals of each sensor into the frequency domain by Fast-Fourier-Transformation

(FFT). Depending on the recorded data the mode shapes are evaluated in the time domain (transient excitation) or in the frequency domain (ambient excitation).

2.2.1. Transient excitation – time domain

If the building can be excited transiently by means of a hammer the induced free vibration response is utilized to identify the dynamic parameters. The procedure of data processing in the time domain is sketched in Figure 2.

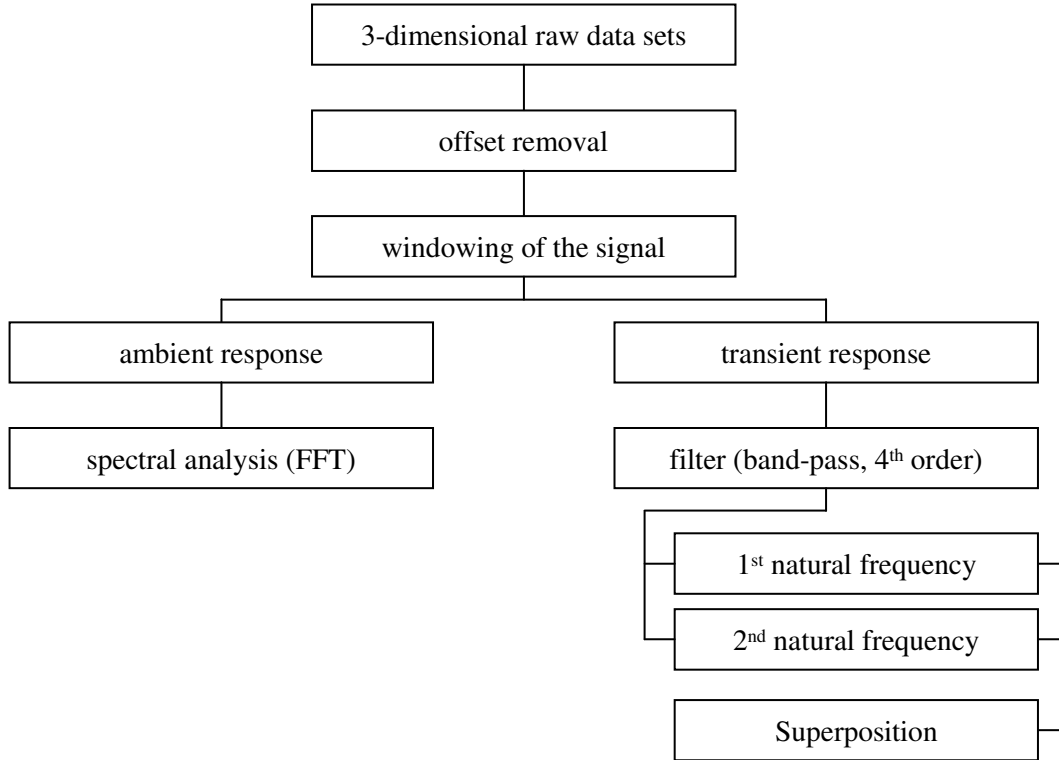


Figure 2: Evaluation of natural frequencies and mode shapes based on transient excitation

The n -th modal component of the undamped free displacement and acceleration response \vec{w}_n and $\ddot{\vec{w}}_n$ respectively, of a multi-degree-of-freedom (MDOF) system differ by the square of the n -th natural circular frequency ω_n^2 [2],

$$\vec{w}_n = \vec{\phi}_n \cos \omega_n t \quad , \quad \ddot{\vec{w}}_n = -\omega_n^2 \vec{\phi}_n \cos \omega_n t \quad (1)$$

In (1) $\vec{\phi}_n$ denotes the n -th mode shape. Since the maximum amplitude of a mode shape is arbitrary the mode shape can be extracted directly from the acceleration response.

The fractions of the response, which vibrate in the natural frequencies of interest, are extracted by filtering the raw signal. Therefore the raw acceleration response is edited by a band-pass filter of 4th order. The frequency band around the considered natural frequency is very narrow, i.e. the upper and lower boundary of the frequency $f_{u,l}$ are selected according to

$$f_{u,l} = f_n \pm \frac{f_n}{100} \quad (2)$$

This procedure is performed for each identified natural frequency. Subsequently, the extracted time history responses of each story is plotted on top of each other, and at certain time

instants the amplitudes are read and combined to the vector $\vec{\phi}_{n,i}$. Note that the floor response must be related to the response recorded with the reference sensor when the measurements of the floor accelerations are conducted at different time instants. Finally, the estimate of the n -th mode shape is determined by averaging,

$$\vec{\phi}_n = \frac{1}{m} \sum_{i=1}^m \vec{\phi}_{n,i} \quad (3)$$

In Figure 3 the evaluation of the first bending mode $\vec{\phi}_1$ of an investigated building structure according to the described procedure is shown.

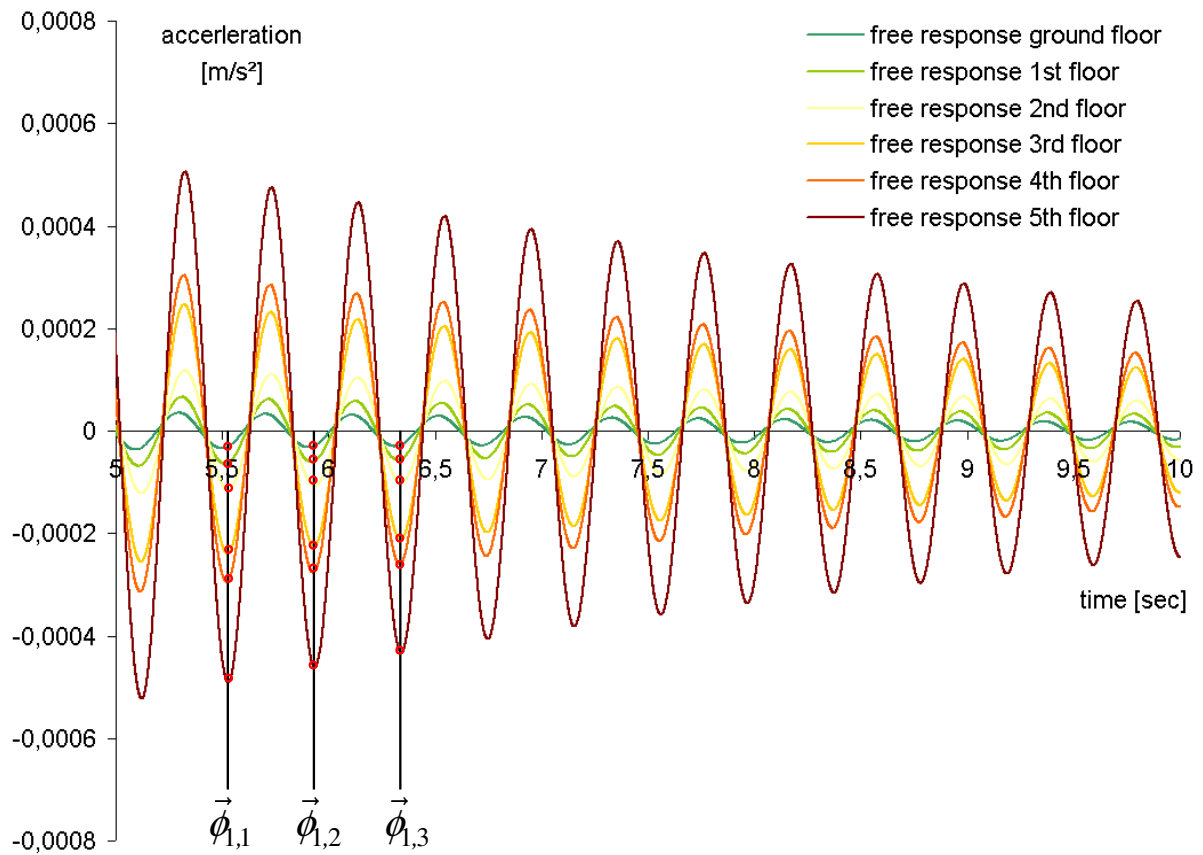


Figure 3: Evaluation of the fundamental mode of a building structure (time domain)

2.2.2. Ambient excitation – frequency domain

If the ambient vibration response is recorded the mode shapes have to be determined in the frequency domain [3]. For the evaluation of the mode shapes it is necessary to evaluate the phase of the acceleration response. Therefore, the phasing of the response signal of each floor of the building needs to be investigated. In order to increase the reliability of the results this should be done simultaneously for each obtained record. The mode shapes are finally averaged for the different recorded signals [3].

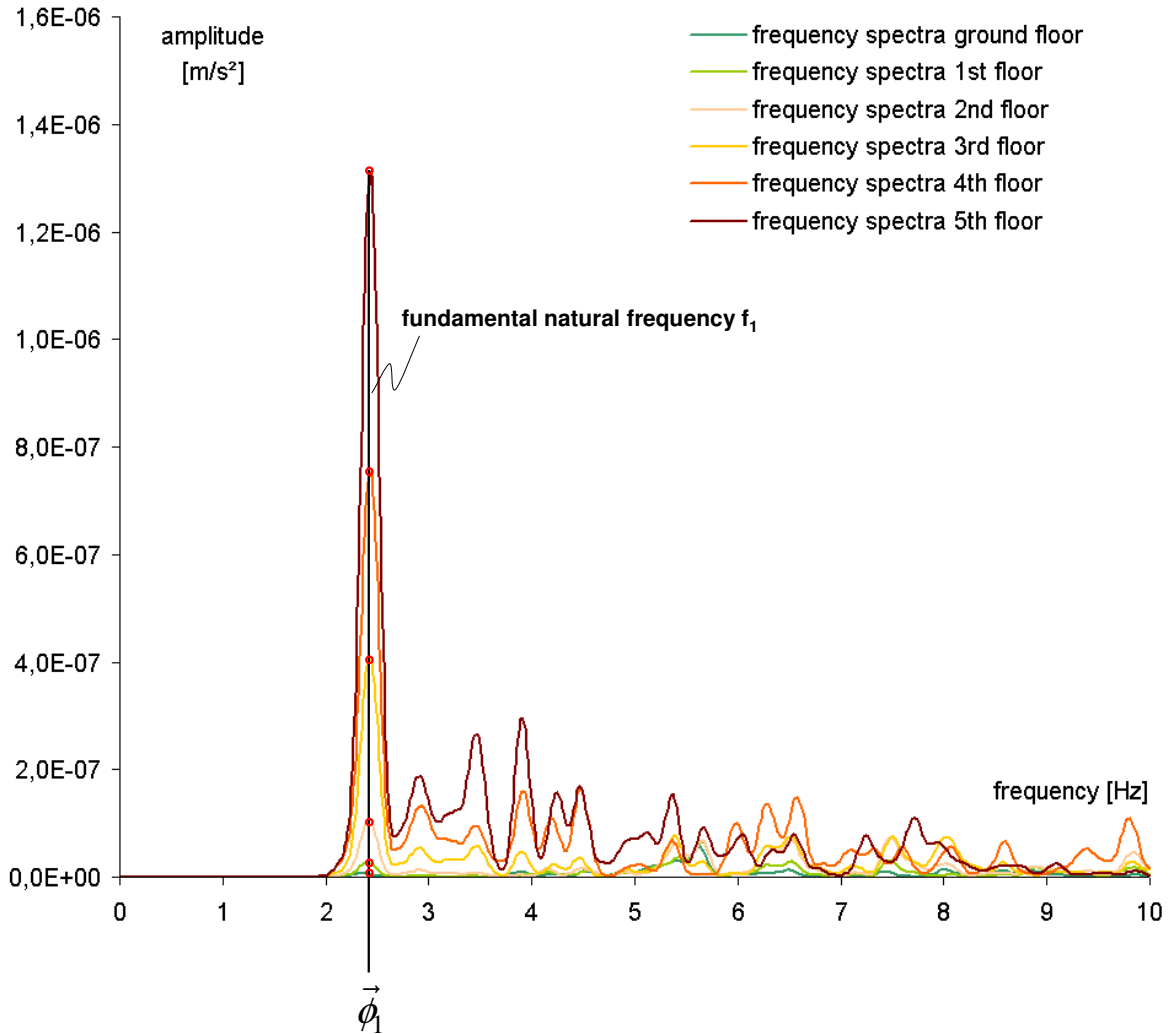


Figure 4: Evaluation of the fundamental mode of a building structure (frequency domain)

2.3 Finite element model update

An estimate of the distributed stiffness of the investigated building is calculated utilizing the equations of motion for a simplified mechanical model. Thereby, the structure is considered as a MDOF system with lumped masses at each story level. The model of the MDOF system is thereby created as an approximation with several assumptions and can lead to differences to the real structure. To improve the accuracy of the system the dynamic parameters are calibrated with the outcomes from in-situ measurements. Therefore a numerical updating procedure is utilized [4].

In general finite element model updating can be performed using direct or iterative methods [5]. The former has the advantages, because no iteration is required and measured data are reproduced exactly. However, if the measured data is inaccurate (or correspond to a highly nonlinear system), a model with no physical meaning may be obtained. In contrast, iterative methods are based on a non-linear penalty function, which is minimized through subsequent linear steps, and more computational time is required.

For the procedure proposed in this paper, a sensitivity-based iterative method is utilized [4]. The computational technique is carried out by VCUPDATE, an iterative updating algorithm implemented in Scilab [6], which is interfaced with the finite element code OpenSees [7].

2.4 Seismic assessment of existing buildings

The performance of the building under seismic loading is estimated by means of the capacity spectrum method [8]. The simplified mechanical model obtained from the finite element model update procedure is subjected to a pushover analysis, which yields the capacity curve of the structure. The pushover analysis facilitates the consideration of material nonlinearities of the structure. It is therefore scheduled to perform large-scale tests on building structures as well as laboratory tests on masonry material in order to get information about the nonlinear behavior of historic buildings. The initial viscous damping of the building is estimated and an appropriate demand spectrum is consulted. The intersection of demand spectrum and capacity curve renders the initial value of the performance point of the building subjected to a given seismic input, as shown in Figure 5. In an iteration procedure the effective viscous damping coefficient $\zeta_{sys,eff}$ is compared with the initial viscous damping value $\zeta_{initial}$ until a certain convergence criterion is reached. Finally the obtained performance point is an appropriate measure for the evaluation of the seismic hazard of the building [8].

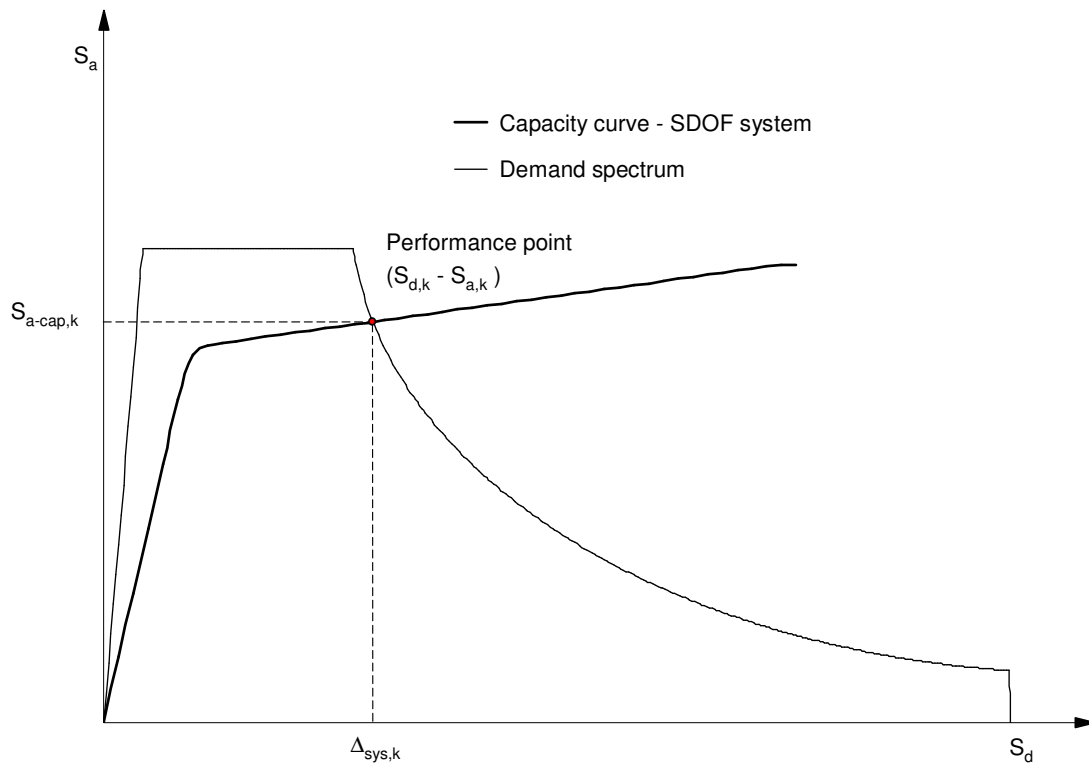


Figure 5: Capacity curve, demand spectrum, and performance point

2.5 Seismic assessment of existing buildings with projected reconstruction

Structural changes of projected reconstructions in existing structures such as remodeling of the attic may be considered by change of mass and stiffness in the mechanical model. This can be done without major effort, because the effect of the structural design features can be estimated very quickly. A pushover analysis renders the capacity curve of the modified model, and seismic assessment analysis is carried out. The impact of various preliminary designs on the seismic vulnerability of the structure can be checked.

3 APPLICATIONS

3.1 Objects

Several existing objects were tested in order to verify the applicability and reliability of the proposed method. The in-situ measurements were preferably performed using transient excitation. In Table 1 the investigated structures, their dimension and employed building material are listed. Furthermore, first and second natural frequencies f_1 and f_2 , respectively, in two directions (E-W: east-west, N-S: north-south) of the objects are given in the same table.

location	dimen- sions [m]	height [m]	building material	$f_{1,E-W}$ [Hz]	$f_{2,E-W}$ [Hz]	$f_{1,N-S}$ [Hz]	$f_{2,N-S}$ [Hz]
1 Riglergasse 10, Vienna	18 x 16	23.2	masonry	2.42	6.75	-	-
2 Diesterwegg. 4, Vienna	12 x 24	16.7	masonry	3.61	11.30	-	-
3 Istanbul I – Fenerbaçe	18 x 31	14.5	RC	5.10	10.20	5.43	19.39
4 Istanbul II – Fenerbaçe	19 x 21	17.0	RC	4.85	-	5.27	10.33
5 Istanbul III – Galatasaray	4 x 14	12.0	masonry	3.02	7.16	-	-
6 Istanbul IV – Fenerbaçe	10 x 20	24.0	RC	1.75	7.15	2.53	10.07
7 Istanbul V – Fenerbaçe	18 x 18	37.0	RC	1.61	7.58	1.63	6.06
8 Bucharest – Hotel Ibis	50 x 17	25.0	RC	-	-	3.03	23.29

Table 1: Investigated structures – general information and natural frequencies determined from measured data.

3.2 Results

In the following object 1 of Table 1 (Riglergasse 10, Vienna) is examined. Both ambient excited and transient excited building response are utilized for the evaluation of this building. Measurements were performed during a long period with a sampling rate of 500 Hz. This large sampling rate was selected to window the signal with small time steps. A part of a record and the windowing of the signal are shown in the Figure 6.

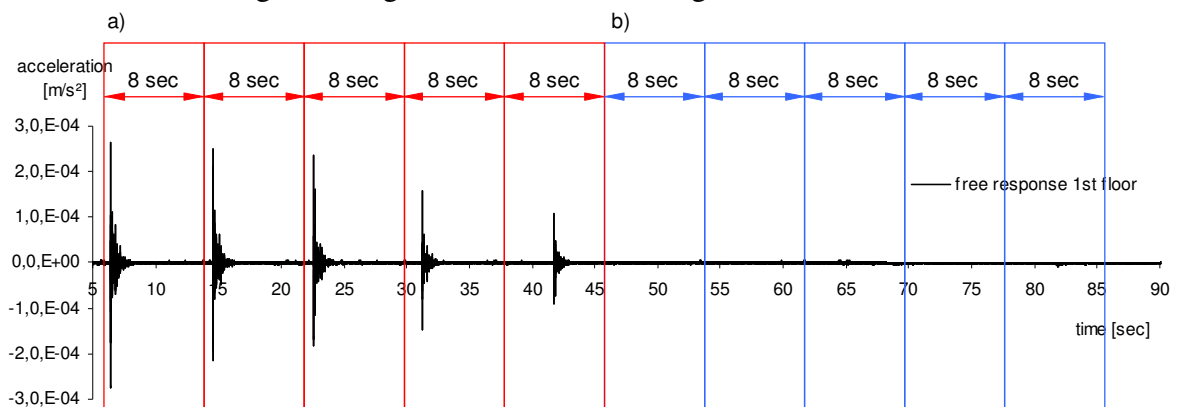


Figure 6: Transient (a) and ambient (b) windows with a length of 8 s for the acceleration record at the first floor of the investigated residential building (Riglergasse 10, 1180 Vienna)

The structural mass was estimated consulting design documents, and lumped to the story levels. The first and second mode shape, the story masses, and the story stiffness are specified

in Figure 7. The stiffness of the mechanical model was determined by application of the mentioned indirect finite element update procedure [4].

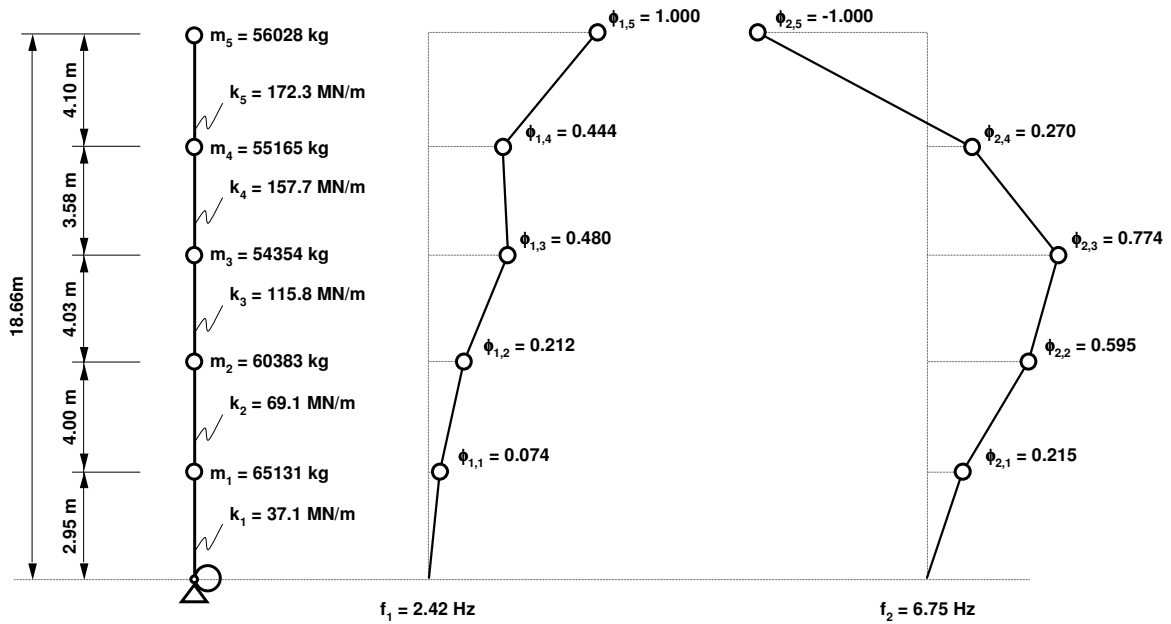


Figure 6: Final model of the investigated residential building (Riglergasse 10, 1180 Vienna), mode shapes (east - west direction) for the corresponding frequencies.

These results constitute the structural input values for the capacity design method. The structural model shown in Figure 7 is subjected to a static pushover analysis.

In order to consider the global nonlinear behavior of the masonry buildings it is scheduled to perform large-scale in-situ pushover tests on real structures. The outcomes of these tests will be utilized to calibrate the numerical pushover analysis. The nonlinear material parameters will be verified using several laboratory-tests on undisturbed masonry specimens.

3.3 Further developments

During the evaluation of the dynamic parameters for the building structures listed in Table 1 some difficulties have emerged, which should be resolved in future research work.

- The evaluation of natural frequencies for residential buildings can be very cumbersome due to the fact that the structure may have no strongly developed vibration behavior. Thus it might be necessary to use different methods for their identification in addition such as the stochastic subspace method [9].
- During the in-situ measurements attention has to be paid to internal excitation (e.g. generators, washing machines), as they can strongly affect the measurement results.
- For the evaluation of the mode shapes in the frequency domain it is advantageous to have ambient signals only. This is hardly to realize because of locally induced vibrations (e.g. by inhabitants).
- The evaluation of mode shapes based on the response induced by impulse loading seems to be more reliable if the structure is rather small, because the initiated free vibrations can be recognized clearly at each sensor location. When there are not enough sensors available to record the induced vibrations simultaneously at all story levels this method leads to reliable results only when the excitation signal can be repeated for each measurement with different locations of the accelerometer.

- For the investigated structures only the first two natural frequencies and mode shapes could be determined. The accuracy of the finite element model update procedure can be increased, if at least the third natural frequency and mode shape is included.

4 CONCLUSIONS

In recent years seismic assessment analysis of existing residential buildings has become a major issue for the construction industry. The release of uniform regulations for whole Europe has led to changes in the validation of the existing structures. Particular the evaluation of the vulnerability of historic residential houses is very difficult to realize. A combined numerical - experimental analysis is the most promising approach to assess these objects. In this paper such a procedure is proposed, which is based on in-situ measurements of the considered object. Evaluation of the recorded vibration response renders the dynamic parameters such as natural frequencies and mode shapes. Procedures in the time and frequencies domain are suggested, depending on the type of measurement. The stiffness of the structure is estimated utilizing a finite element model update procedure. Subsequently, the seismic vulnerability of the building is verified utilizing capacity spectra. The structural resistance of existing buildings after reconstruction, such as erection of additional apartments in empty attics, can be done by the same procedure.

REFERENCES

- [1] Municipality of Vienna, Division 37 (MA 37), Instructions for authors of static documents about procedure and content of static initial dimensioning and the engineers finding at building construction according § 60 section 1 lit. a (new constructions, additions, remodeling), b (other building systems) and c (modification and repair of buildings and building systems) BO. April 2006, in German. ("Magistratsabteilung 37 (MA 37), Merkblatt für die Verfasser der statischen Unterlagen über Vorgangsweise und Inhalt der statischen Vorbemessung und des Ingenieurbefundes bei Bauführungen gemäß § 60 Abs. 1 lit. a (Neu-, Zu- und Umbau), b (sonstige bauliche Anlagen) und c (Änderung und Instandsetzung von Gebäuden und baulichen Anlagen) BO. April 2006.
- [2] A. Chopra, *Dynamics of Structures*, 3rd Edition. Prentice Hall, 2006.
- [3] H. Wenzel, D. Pichler, *Ambient Vibration Monitoring*. Wiley, 2005.
- [4] A. Mordini, K. Savov, H. Wenzel, Damage detection on stay cables using an open source-based framework for Finite Element Model Updating. *Structural Health Monitoring*, accepted for publication.
- [5] M.I. Friswell, J.E. Mottershead, *Finite Element Model Updating in Structural Dynamics*. Kluwer Academic, 1995.
- [6] Scilab, A Free Scientific Software Package, <http://www.scilab.org>.
- [7] OpenSees, Open System for Earthquake Engineering Simulation, <http://opensees.berkeley.edu>.
- [8] Applied Technology Council, *ATC-40: Seismic evaluation and retrofit of concrete buildings*. Report No. SSC 96-01, 1996.
- [9] B. Peeters, *System identification and damage detection in civil engineering*. PhD thesis, KU Leuven, 2000.