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ORIGINAL RESEARCH PAPER

Rapid seismic evaluation of historic brick-masonry buildings in Vienna (Austria) based on visual screening

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Abstract The present paper addresses seismic assessment of historic brick-masonry buildings located in the city of Vienna based on rapid-visual-screening (RVS). The RVS methodology has been adopted for this specific type of buildings considering their consistent typology and consequently enhancing the validity and quality of the seismic assessment. In this context, structure-relevant parameters such as regularity of the inspected building, its state of preservation and geometry are evaluated. Additionally, the human and economic impact of earthquake-induced damage on the object is integrated assessing damage relevant factors such as the number of exposed persons and the importance of the object for the public. Based on the derived score of each of these two sets of parameters the inspected building is classified into one of four vulnerability classes. Furthermore, the damage potential of a seismic event comparable with the L'Aquila 2009 earthquake is predicted correlating the results of the RVS methodology and damage grades according to EMS-98. In a large-scale in-situ investigation a set of 375 buildings within the 20th district of Vienna was seismically assessed. The resulting maps of damage scenarios give useful information for emergency and evacuation planning as well as for identification of critical objects vulnerable to seismic loading.

Keywords Damage scenario · Historic brick-masonry buildings · Rapid-visual-screening · Vienna · Vulnerability class

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1 Introduction

1.1 Objective

The city of Vienna is the political and economic capital of the Republic of Austria, and its 1.71 million inhabitants (as of 2011) represent about one fifth of the total population of Austria. The city center of Vienna is dominated by historic residential brick-masonry buildings, which were constructed during a major urban expansion in the period between 1848 and 1918, referred to as "Gründerzeit". At present, one third of the complete building stock in the urban area of Vienna, i.e. 32,000 objects, consists of these Viennese brick-masonry buildings. They shape the urban image of Vienna, and thus, make the city attractive to visitors. As an example, Fig. 1 shows the façade of a representative Viennese brick-masonry building. Additionally, renovation of these buildings and conversion of their empty attics into high-quality apartments allows an environment-friendly concentration of the city population in the city center without development of agricultural areas.

Vienna is located in the Vienna Basin, where a fault shows continued fault activity (Hinsch and Decker 2003). The Vienna Basin is classified as a moderate seismic zone. The focal depth of most earthquakes is about 7–8 km. However, studies of historic earthquakes have revealed that in the past the seismic hazard of the Vienna Basin, and thus also of the city of Vienna, has been underpredicted. In the available observation time several strong earthquakes with intensity larger than 7 (EMS-98 scale according to Grünthal 1998) were discovered or re-evaluated. The most recent severe earthquake with an intensity of 7–8 took place on April 16, 1972 in the village of Seebenstein, which is located in the southern part of the Vienna Basin. The impact of this earthquake could also be felt in Vienna, where several buildings and numerous chimneys were damaged. The last earthquake with an intensity of 8 occurred on October 8, 1927 in the village of Schwadorf, southeast of Vienna. The earthquake caused severe damage to the property in Schwadorf and in the neighborhood. The strongest observed earthquake in the Vienna Basin is reported from 1590 close to the village of Neulengbach, which exhibited an intensity of 9 and a moment magnitude of $M_w = 6.2$. This seismic event, which may be considered as the strongest possible seismic event in the Vienna Basin (Hinsch and Decker 2003), is comparable with the L'Aquila 2009 earthquake because site condition and focal depth are similar.

Fig. 1 Front of the characteristic Viennese brick-masonry building "Riglergasse 10"

Hence, the national version of Eurocode 8 (EC8 2006) imposes additional seismic demands on these structures compared to the previous standards. Additionally, more recently, the reliability of the structural safety of these buildings against severe earthquake-induced damage and ultimately collapse was subject of a huge debate among civil engineers and authorities of the municipality of Vienna. As a consequence, rehabilitation and reconstruction of Vienna brick-masonry buildings has drastically declined leading to huge economic losses.

In 2006 the Austrian national research project SEISMID (Achs et al. 2011) was launched aiming, among others, at revealing the seismic vulnerability of these historic objects. One of the main objectives of this project is the development of a rapid-visual-screening (RVS) methodology specified for the comprehensive seismic evaluation of Viennese brick-masonry buildings, which aims at realistically estimating the vulnerability of these historic objects under seismic loading. This methodology facilitates classification of objects of a larger area with respect to their seismic vulnerability. Furthermore, another goal of this research is the prediction of the damage potential of these historic objects under seismic loading comparable with the L'Aquila 2009 earthquake by correlating the results of the proposed RVS methodology and damage grades according to EMS-98. The derived classification of the buildings may serve directly for earthquake-induced damage scenarios for Viennese urban areas with a large stock of historic brick-masonry buildings, or it may provide a basis for a more detailed investigation of objects identified to be potentially vulnerable against seismic action. Moreover, rescue and safety planning in an emergency is supported.

1.2 Prevalent seismic assessment methodologies based on rapid-visual-screening

In the last few years different methodologies for the seismic assessment and classification of existing buildings were developed (Calvi et al. 2006). Many of them, so-called RVS methodologies, are based on visual inspection of the buildings using predefined forms. Their main advantage is the fast and elementary implementation, which allows the user to evaluate a large amount of buildings in a relatively short period of time. Particularly in areas with high seismicity the application of RVS techniques is widespread.

One of the basic documents, developed and used in the United States of America, is the RVS methodology described in the FEMA 154 (2002) handbook for seismic evaluation of existing buildings. This method has already been used for years and is an important basis for various international techniques. In particular the method is based on a scoring system, in which different building parameters are classified and benchmarked.

Apart from the RVS procedures in the United States of America several other techniques were developed in different countries. The Japanese technique (JBDPA 2001) is based on the so-called Seismic Index (IS), which describes the resisting earthquake capacity of a story and is estimated from the strength and ductility of the building, the regularity of the building and a certain time index. In contrast, the RVS procedure applied in Canada (NRCC 1993) accounts for structural parameters, such as the stiffness and the regularity of the building, as well as for non-structural parameters, the foundation of the building, building occupancy, importance of the building, and falling hazards. Compared to other countries, India has a very large amount of existing buildings of different types, which led to the development of several RVS procedures in the last few years (Jain et al. 2010; Gogoi 2010).

Many of the European RVS procedures were developed in Greece (OASP 2000; Demartinos and Dristos 2006) and in Turkey (Sen 2010; Hassan and Sozen 1997; Ozdemir and Taskin 2006), with the investigated masonry buildings of the high seismicity area of Istanbul (Vatan and Arun 2010; Erberik 2010) being of interest for the proposed RVS procedure developed for Viennese brick-masonry buildings. The Swiss Standard SIA 2018 (2004) applies a three-stage concept for evaluating the seismic risk. In the first stage, based on the building plan and visual inspection, the most important elements of the building and the seismic risk are roughly assessed. In the second stage the seismic risk of some selected objects is studied in more detail. In the third stage strengthening measures are developed for a limited number of vulnerable buildings.

Some fundamentals of the methodology described in this paper were developed for historic masonry buildings in Italy (D'Ayala and Speranza 2002) and Portugal (Ferreira et al. 2010). On the one hand, the assessment of brick-masonry facades can be directly applied by quantifying the building geometries (D'Ayala and Speranza 2002). On the other hand, the correlation of the physical seismic vulnerability with damage grades from EMS-98 (Grünthal 1998) based on post seismic damage observation gives a reliable estimation of the possible extent of damage according to Ferreira et al. (2010). Among the numerous other RVS procedures, methods developed in Germany (Meskouris et al. 2001; Sadegh-Azar 2002) are of particular interest for the proposed RVS methodology in Vienna, as they were applied on similar historic buildings located in areas with comparable seismicity.

2 Assessment of the seismic vulnerability

2.1 Building characteristics of Viennese brick-masonry building

Viennese brick-masonry buildings usually have four to five stories. The load-bearing walls were built of brick-masonry. In this process solid bricks of the so-called "old Austrian" format with a dimension of 290 × 140 × 65 mm arranged in various patterns were placed in mortar. In historic building regulations (Municipality of Vienna 1892) it was specified that structural analysis could be skipped if a minimum wall thickness was met. Thus, compared to modern buildings the load-bearing walls were relatively thick. Partition walls were also built of brick-masonry with a thickness of 14 cm. Since, in an untouched building, the latter are vertically continuous through all floors, they increase the lateral stiffness of the object. Above the basement massive brick vaults were constructed, which provides the basement with a large lateral stiffness. Timber was used for the ceilings and the roof structure. The ceilings were composed of timber beams, over which board flooring was laid. The load-bearing beams were placed perpendicular to the exterior and interior load-bearing walls. Usually, they were connected to the walls only in direction of the beam axis. As an example, Fig. 2a depicts the floor plan of the 2nd, 3rd and 4th story of the object "Riglergasse 10". A section of this object is shown in Fig. 2b compare also with Fig. 1.

Typically, the basement is relatively rigid, and thus, only the structure above the brick-vaults is vulnerable against seismic loads. When located in between two buildings, these objects are particularly vulnerable in transversal direction (denoted as x-direction, Fig. 2a), because the resistance against horizontal loads is provided only by the gable walls, the walls of the staircase, and partition walls, compare with Fig. 2a. The timber floors of an untouched building are relatively flexible with questionable floor-wall connection. Therefore, the assumption that they are acting as rigid diaphragms and distributing the inertia forces from the floors onto the walls is less valid compared to, for example, composite timber-reinforced concrete floors (Lang 2002). Consequently, the earthquake resistance of an untouched building against global collapse is governed predominately by the brick-masonry gable walls, the load-bearing walls of the staircase, and the lateral partition walls, if they are continuous from their support at the brick-vaults to the attic.

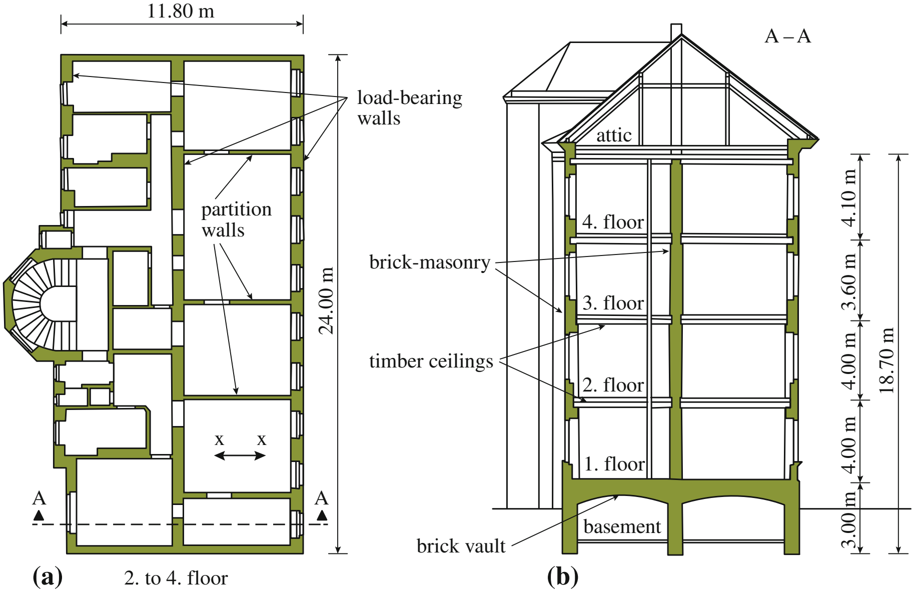


Fig. 2 **a** Floor plan of the 2nd, 3rd floor and 4th floor, and **b** section of the object "Riglergasse 10"

In the last century the first floors of Viennese brick-masonry buildings located at outdoor malls and shopping streets were converted into shops and stores. Retail space generally requires large areas, and thus, internal load-bearing walls and partition walls were removed and replaced by columns, which exhibit minor lateral resistance against horizontal loads. Furthermore, stiffness and strength of the external load-bearing walls facing the street front were reduced to make space for large shop windows available. Merging of smaller residential units into larger apartments or conversion into offices gave rise to the extraction of partition walls in the upper stories, which, in an intact building, considerably contribute to the lateral building resistance. These vertical and horizontal irregularities usually imposed later make these buildings particularly vulnerable to seismic loading.

2.2 Basic data

As most of the international RVS methodologies are focused on buildings with a consistent topology, an adopted method with specific controlling parameters for the historic brick-masonry buildings in Vienna had to be developed. Fundamental approaches from provisions, standards, and existing national and international RVS procedures such as SIA 2018 (2004) and FEMA 154 (2002), which are formulated in a quite general manner, were adapted to the needs of the considered building type. The proposed RVS methodology is based on comprehensive preliminary in-situ inspections and measurements (Achs 2011) on Viennese brick-masonry buildings. It considers the results of a detailed study of historic documents such as Viennese building codes from the nineteenth century (Building Code for Vienna 1859, 1869, 1883; Municipality of Vienna 1892), and historic plans and maps. Furthermore, findings of more recent national investigations (Flesch et al. 2005; ÖIBI 2009; Rusnov 2006) on this specific building type entered this RVS methodology. Particularly, several approaches from a guideline (ÖIBI 2009) for the in-situ assessment of the state of preservation of the structural system of existing Viennese buildings were adjusted.

2.3 Elementary parameters of the vulnerability assessment

The seismic vulnerability is the internal risk factor of the considered exposed element such as a building, or at a larger level, an urban area with a building stock of similar characteristics to seismic hazard (Barbat et al. 2010). It comprises not only the *physical seismic vulnerability*, which is related to the seismic resistance of the structure itself, but also the *socio-economic vulnerability*, which considers the social, economic and political impact of earthquake induced structural damage on the community. However, most studies in earthquake engineering implicitly refer to the *physical seismic vulnerability* only when the term *seismic vulnerability* is used.

In the present study the *comprehensive seismic vulnerability* of Viennese brick-masonry buildings, i.e. both the *physical* and *socio-economic vulnerability*, is evaluated. Consequently, the proposed RVS methodology is based on two sets of parameters (SIA 2018 2004) that comprise

- a set of nine individual structural parameters, which control the impact of certain structural parts on the resistance of the considered building against seismic action, and
- a set of five parameters, which characterize the social and economic impact on the community, if the building is damaged in an earthquake.

In Table 1 the individual structural parameters, denoted as $S_{01}, S_{02}, \ldots, S_{09}$, are described in more detail. Thereby, the regularity in plan and elevation, the detailed connection between ceilings and brick-walls, potential local failure of the façades and secondary structures, condition of soil and foundation, and the state of preservation are evaluated. Parameter S_{08}, which is related to the foundation, and parameter S_{09}, which refers to the state of preservation, are described in more detail in Tables 2 and 3, respectively. Depending on the actual situation and condition of the considered building, each of the individual parameters is benchmarked, compare with Table 1. A low score implies that the corresponding parameter does not significantly impair the earthquake resistance of the considered building. The higher the largest possible score the more important is the corresponding structural parameter for a building's overall physical seismic vulnerability. Thus, as it can be read from Table 1, the most important individual parameters, which can be related directly to earthquake induced structural damage, are the vertical and horizontal regularity of the building in elevation and the state of preservation. The possible high score related to the regularity in elevation (parameter S_{03}) takes into account the considerable impairment of the lateral building resistance when shear walls etc. were removed. Eventually, the sum of the individual scores of parameters S_{01} to S_{09} yields the overall Structural Parameter SP of the inspected building, which evaluates the building's physical vulnerability to earthquake-induced damage.

The second set of parameters, denoted as $D_{01}, D_{02}, \ldots, D_{05}$, is summarized as Damage Relevance DR. An overview of the content of the damage relevance as well as the description and quantification of several parameters are presented in Table 4. The main parameter of the damage relevance, D_{01}, is the number of exposed persons within the inspected object. Further damage relevant parameters evaluate the public importance of the building (hospital, school, ordinary residential building), its economic importance, the material assets, and the effects of damage on the direct environment. The derived Damage Relevance DR, which is the sum of the individual scores of parameters D_{01} to D_{05}, is a measure of the socio-economic vulnerability of the inspected object.

Table 1 Set of individual parameters describing the structural parameter *SP*

Parameter	Description		Benchmark
S_{01}	Seismic zone according to EC8 (2006)		
Seismic hazard	Vienna, northeast of the river Danube	$S_{01} = 1.0$	1.0–2.0
	Vienna, southwest of the river Danube	$S_{01} = 2.0$	
S_{02} Regularity in plan	Classification of the regularity in plan according to EC8 (2005)		
	Regular plan, length to width ratio in plan <4	$S_{02} = 1.0$	1.0–10.0
	Regular plan, length to width ratio in plan >4	$S_{02} = 5.0$	
	Irregular plan, length to width ratio in plan <4	$S_{02} = 5.0$	
	Irregular plan, length to width ratio in plan >4	$S_{02} = 10.0$	
S_{03} Regularity in elevation	Vertical irregularities with particular attention to soft stories		
	All partition walls and shear elements preserved	$S_{03} = 1.0$	1.0–100.0
	Some partition walls removed/shear elements preserved	$S_{03} = 20.0$	
	All partition walls removed/shear elements preserved	$S_{03} = 50.0$	
	All partition walls and shear elements replaced by columns	$S_{03} = 100.0$	
S_{04}	Evaluation of the ceiling-wall connection		
Horizontal stiffness	Connection of timber ceilings and walls with steel ties		
	Existing and in good condition	$S_{04,1} = 1.0$	1.0–25.0
	Non-existent, not identified, or in bad condition	$S_{04,1} = 5.0$	
	Brick faults above the basement		
	Existing and in good condition	$S_{04,2} = 1.0$	
	Non-existent, not identified, or in bad condition	$S_{04,2} = 5.0$	
		$S_{04} = S_{04,1} \times S_{04,2}$	
S_{05} Local failure	Potential local failure mechanism of the façades (Achs 2011) according to the load factor λ_0 (D'Ayala and Speranza 2002)		
	$\lambda_0 < 0.25$	$S_{05} = 1.0$	1.0–20.0
	$0.25 \leq \lambda_0 < 0.50$	$S_{05} = 5.0$	
	$0.50 \leq \lambda_0 < 0.70$	$S_{05} = 10.0$	
	$\lambda_0 \geq 0.70$	$S_{05} = 20.0$	
S_{06} Secondary structures	Exposed secondary structures such as chimneys, sculptures and statues of the façade, cornices, etc.		
	Number Exposure to the public		
	0	$S_{06} = 0$	0–20.0
	<3 low/high	$S_{06} = 1.0/5.0$	
	3–6 low/high	$S_{06} = 5.0/10.0$	
	>6 low/high	$S_{06} = 10.0/20.0$	

Table 1 continued

Parameter	Description		Benchmark
S_{07} Soil condition	Local soil conditions classified according to EC8 (2005)		
	Soil class A	$S_{07} = 1.0$	1.0–10.0
	Soil class B	$S_{07} = 2.5$	
	Soil class C	$S_{07} = 5.0$	
	Soil class D	$S_{07} = 7.5$	
	Soil class E	$S_{07} = 10.0$	
S_{08} Foundation	Score depending on the location of the building and type of foundation For details see Table 2		1.0–10.0
S_{09} State of preservation	State of preservation of the structure (ceilings, columns, brick-masonry, etc.) For details see Table 3		0–30.0
Structural Parameter (total score) $SP = \sum_{i=1}^{9} S_{0i}$			

Table 2 Foundation: parameter S_{08}

Foundation type	1st, 3rd–19th, 23rd district of Vienna	2nd, 20th–22nd district of Vienna; building located in the area of historic waters
Shallow foundation, embedding depth ≥0.65 m	$S_{08} = 1.0$	$S_{08} = 2.5$
Shallow foundation, embedding depth <0.65 m	$S_{08} = 2.5$	$S_{08} = 5.0$
Wood pile foundation	$S_{08} = 5.0$	$S_{08} = 10.0$
Unknown	$S_{08} = 2.5$	$S_{08} = 10.0$

2.4 Classification

The categorization and prioritization of Viennese brick-masonry buildings is based on the combination of the Damage Relevance *DR* and the Structural Parameter *SP*. To this end four *vulnerability classes* have been adopted (Achs 2011), depending on the benchmark of *SP* and *DR* as specified subsequently, in an effort to assess the comprehensive seismic vulnerability of the inspected building:

$$\text{Vulnerability Class I}(VCI) : SP < 50 \text{ and } DR < 50$$

$$\text{Vulnerability Class II } (VCII) : 80 > SP \geq 50 \text{ and } DR < 100$$

$$\text{or}$$

$$100 > DR \geq 50 \text{ and } SP < 80$$

Table 3 State of preservation: parameter S_{09}

Extent of damage	Very high	High	Moderate	Low	Very low	No damage
Basic score BS_{09}	15.0	10.0	7.5	5.0	2.5	0

Structural element	Factor FS_{09}
Roof structure (ingress of water, damaged connections)	1.00
Cornice (cracks, deposits on cornice, condition of the eaves purlin)	1.25
Top ceiling (moisture, other damage)	1.75
Standard stories: ingress of water	1.75
Standard stories: cracks	1.25
Staircase (damage at the support of the stairs, joint between the stairs, condition of the supports of the stair head)	1.25
First floor (damage of load-bearing elements)	2.00
Basement	1.75
Building equipment and appliances (connections, condition)	1.50

$S_{09} = \max(BS_{09} \times FS_{09})$

$$\begin{aligned}
&\text{Vulnerability Class III } (VC\text{III}) : 140 > SP \geq 80 \text{ and } DR < 150\\
&\qquad\qquad\text{or}\\
&\qquad 150 > DR \geq 100 \text{ and } SP < 140\\
&\text{Vulnerability Class IV } (VC\text{IV}) : SP \geq 140\\
&\qquad\qquad\text{or}\\
&\qquad DR \geq 150
\end{aligned} \tag{1}$$

If a building is categorized into Vulnerability Class *VC*I, its damage potential under seismic loading is low. In contrast, the seismic risk of a building in Vulnerability Class *VC*IV must be assessed in more detail because it is very likely vulnerable to earthquake excitation. Figure 3 visualizes the separation of the individual vulnerability classes as a function of the Damage Relevance *DR* and the Structural Parameter *SP*.

The limits of the individual vulnerability classes are based on a calibration of the outcomes of an initial application of this RVS methodology on a set of 18 Viennese brick-masonry buildings. In this connection the state of preservation, structural system, dynamic behavior, and socio-economic parameters of those buildings were known in advance from detailed in-situ investigations, experimental tests and computations. The buildings distributed across the historic city center of Vienna represent a wide range of evaluation parameter possibilities. A comprehensive description of those buildings, results of the application of the RVS methodology, and outcomes of the calibration are given in Achs (2011).

In addition to the comprehensive seismic vulnerability it is of interest to disclose the physical and socio-economic seismic vulnerability of the inspected object separately.

In order to quantify the physical seismic vulnerability of Viennese brick-masonry buildings a classification into four *structural classes* has been conducted, however, considering the final score of the Structural Parameter *SP* only. Structural Classes *SC*I, *SC*II, *SC*III, and *SC*IV are defined as:

Table 4 Set of parameters describing the Damage Relevance *DR*

Parameter	Description		Benchmark
D_{01} Human exposure	Number of endangered individuals within the inspected object(estimation accepted in case of limited accessibility of the inspected object.)		No of individuals
D_{02} Public importance	Importance of the inspected object for the public according to EC8 (2005) ranging from importance class II to IV.		
	II: Ordinary residential buildings	$D_{02} = 1.0$	1.0–50.0
	III: Schools, assembly rooms, etc.	$D_{02} = 10.0$	
	IV: Hospitals, etc.	$D_{02} = 50.0$	
D_{03} Economic importance	Useable living area (ULA)multiplied by the potential price per m^2, and consideration of the remaining life-time (RLT) of the inspected object.		$\frac{ULA \cdot Price[\text{Euro}]}{100{,}000} \cdot \frac{RLT}{25}$
D_{04} Material assets	Real assets at risk (building content)		
	Low risk: residential buildings	$D_{04} = 1.0$	1.0–10.0
	Medium risk: archives and libraries	$D_{04} = 5.0$	
	High risk: museums, etc.	$D_{04} = 10.0$	
D_{05} Effects on the environment	Effects of building collapse or partial collapse on the environment of the building		
	Low exposure	$D_{05} = 1.0$	1.0–10.0
	Medium exposure: exposure of pedestrians	$D_{05} = 5.0$	
	High exposure: exposure of important infrastructure	$D_{05} = 10.0$	
Damage Relevance (total score) $DR = \sum_{i=1}^{5} D_i$			

$$\begin{aligned}
&\text{Structural Class I } (SC\text{I}) : SP < 50\\
&\text{Structural Class II } (SC\text{II}) : 80 > SP \geq 50\\
&\text{Structural Class III } (SC\text{III}) : 140 > SP \geq 80\\
&\text{Structural Class IV } (SC\text{IV}) : SP \geq 140
\end{aligned} \tag{2}$$

Equation (2) correspond to Eq. (1), however, considering the conditions for the Structural Parameter *SP* only. Again, the higher the structural class, in which the inspected object is categorized, the larger is the physical vulnerability of the building structure against seismic action.

Accordingly, four relevance classes, denoted as *RC*I, *RC*II, *RC*III, *RC*IV, respectively, were defined in an effort to classify the socio-economic vulnerability. The individual relevance classes are separated by the conditions given in Eq. (1) concerning the Damage Relevance *DR* only:

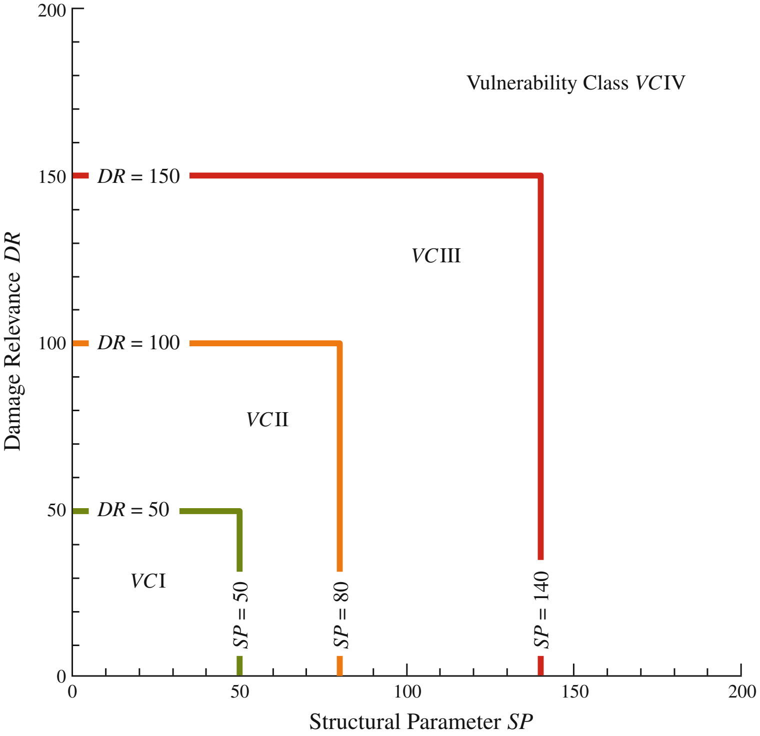


Fig. 3 Vulnerability classes presented as a function of the Structural Parameter *SP* and the Damage Relevance *DR*

$$
\begin{aligned}
&\text{Relevance Class I } (RC\text{I}) : DR < 50\\
&\text{Relevance Class II } (RC\text{II}) : 100 > DR \geq 50\\
&\text{Relevance Class III } (RC\text{III}) : 150 > DR \geq 100\\
&\text{Relevance Class IV } (RC\text{IV}) : DR \geq 150
\end{aligned}
\tag{3}
$$

2.5 Inspection form

A standardized inspection form has been prepared to simplify on-site visual screening of Viennese brick-masonry buildings. The form guides the surveyor through the screening procedure step-by-step, and it supports the inspection. After digitalization of the data the Structural Parameter *SP*, the Damage Relevance *DR* and the classification of the inspected building into a particular vulnerability class, structural class, and relevance class is evaluated automatically. For details refer to Achs (2011).

3 Damage scenarios

The seismic risk of a structure is assessed correlating its physical seismic vulnerability with the earthquake hazard. Generally, this correlation depends on various parameters and can be determined with considerable efforts only. Particularly for historic buildings the prediction of earthquake-induced damage is difficult, even if advanced methods of analysis are used. Alternatively, observations from past earthquakes and post-earthquake assessment reports can be utilized to correlate the results from RVS methodologies with a possible damage scenario under seismic action. This method can be used if no particular vulnerability curves of the inspected buildings are available (Ferreira et al. 2010). Subsequently, such a technique is used for the damage assessment of the considered Viennese brick-masonry buildings subjected to a particular earthquake. It is based on the categorization in structural classes as an outcome of the proposed RVS methodology describing its physical vulnerability.

For the present study, the damage induced by the 2009 earthquake, which hit the city of L'Aquila in the Abruzzo region in Italy, was chosen. This seismic event with a moment magnitude $M_w = 6.3$ and focal depth of 10 km (Celik and Sesigur 2010) can be compared with the largest possible earthquake, which might occur in the Vienna Basin (Hinsch and Decker 2003). The site conditions and the historic building stock of L'Aquila are similar to the ones in Vienna.

Thus, post-seismic damage on historic residential brick-masonry buildings observed after the L'Aquila earthquake is examined. The main outcome of the study of post-earthquake reports of the L'Aquila earthquake (e.g. D'Ayala and Paganoni 2011; Tertulliani et al. 2011; Celik and Sesigur 2010; Alarcon et al. 2010) is that some of the proposed structural parameters for historic residential brick-masonry buildings in Vienna can be directly related to seismic damage. The most important parameters are apparently the regularity in elevation, soft stories, the detailed design of connections between timber ceilings and bearing walls, number and size of openings in the shear walls, and the state of preservation of the affected building structure. Most of the damaged buildings had retail areas on the first floors. On the other hand, a well-preserved building without irregularities in plan and elevation was subject to moderate damage only.

The proposed classification of earthquake-induced damage on Viennese brick-masonry buildings is based on the damage description of the European Macroseismic Scale EMS-98 (Grünthal 1998). The EMS-98 distinguishes between five damage grades depending on the observed damage on masonry buildings, as outlined in Table 5 (Grünthal 1998). Damage Grade 1 refers to a building, which exhibits negligible to slight damage. At the other end, a masonry building classified into Damage Grade 5 is in a condition of near-collapse to total collapse.

The comparison between damages occurred in L'Aquila (D'Ayala and Paganoni 2011; Tertulliani et al. 2011; Celik and Sesigur 2010; Alarcon et al. 2010), the damage description of the EMS-98 Scale, and the physical vulnerability as outcomes of the proposed RVS methodology lead to the proposed relations compiled in Table 6. Therein, the structural classes based on the physical vulnerability of the inspected object, are correlated with predicted damage grades according to EMS-98 for an earthquake of moment magnitude $M_w = 6.3$. It is obvious that buildings with high regularity in plan and elevation and a very good state of preservation, and thus classified into Structural Class *SC*I, should resist an earthquake similar to the one that occurred in L'Aquila with moderate damages (Celik and Sesigur 2010). On the other hand, building structures with high irregularity in elevation and potential soft stories, which are generally in a poor state of preservation and therefore classified into Structural Class *SC*IV, may exhibit very heavy damages up to total destruction if exposed to a comparable earthquake. In between the buildings with slight or moderate irregularity in plan and elevation and moderate up to good state of preservation, which are categorized into Structural Class *SC*II or *SC*III, respectively, are predicted to show different grades of damage according to EMS-98, ranging from moderate to very heavy damage.

Table 5 Classification of masonry buildings according to EMS-98 (Grünthal 1998)

Damage grade according to EMS-98	Description of damage
1	Negligible to slight damage (*no structural damage, slight non-structural damage*) Hair-line cracks in very few walls Drop of small pieces of plaster only Drop of loose stones from upper parts of buildings in very few cases
2	Moderate damage (*slight structural damage, moderate non-structural damage*) Cracks in many walls Drop of fairly large pieces of plaster Partial collapse of chimneys
3	Substantial to heavy damage (*moderate structural damage, heavy non-structural damage*) Large and extensive cracks in most walls Detachment of roof tiles Fracture of chimneys at the roof line Failure of individual non-structural elements (partitions, gable walls)
4	Very heavy damage (*heavy structural damage, very heavy non-structural damage*) Serious failure of walls Partial structural failure of roofs and floors
5	Destruction (*very heavy structural damage*) Total or near total collapse

Table 6 Correlation between Structural Parameter *SP* and damage grades based on EMS-98

Structural class	Conditions of classification	Predicted damage grade based on EMS-98	Relevant structural conditions
*SC*I	$SP < 50$	2	High regularity in plan and elevation; excellent state of preservation
*SC*II	$80 > SP \geq 50$	2–3	Slight irregularity in plan and elevation; good state of preservation
*SC*III	$140 > SP \geq 80$	3–4	Moderate irregularity in elevation; subsequently removed bearing elements; moderate state of preservation
*SC*IV	$SP \geq 140$	4–5	High irregularity in elevation; soft-story; in general poor state of preservation

4 Application

4.1 Test object “Währinger Gürtel 164”

4.1.1 Description

Based on the proposed methodology the seismic vulnerability of the object “Währinger Gürtel 164” was assessed. This historic five-story brick-masonry building was located in the 9th

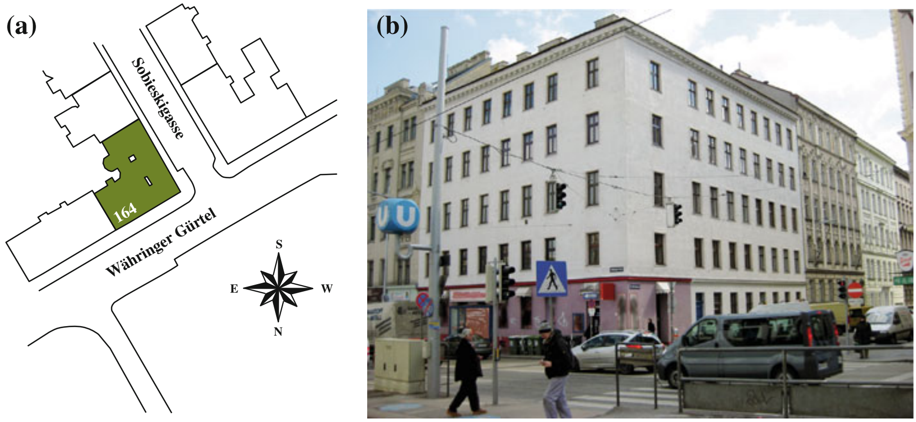


Fig. 4 **a** Overview of the investigated object "Währinger Gürtel 164", **b** photograph of the test object

district of Vienna at the intersection of two streets named "Währinger Gürtel" and "Sobieskigasse", as shown in Fig. 4a. It was constructed in 1891 as a residential building, and had two perpendicularly arranged wings resting on a basement. Figure 4b shows a photograph of the test object facing both street fronts. A vaulted brick-slab separated horizontally the basement and the first floor. The brick-masonry load-bearing walls had a thickness up to 75 cm, the thickness of the partition walls was 15 cm.

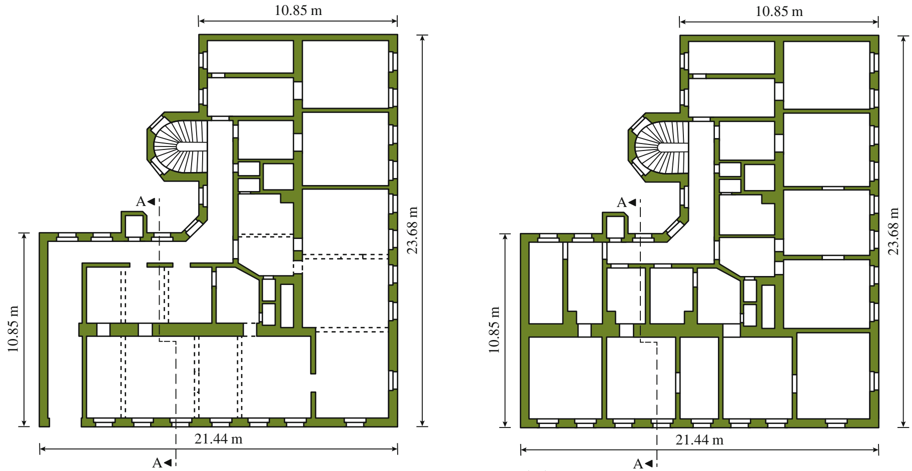
In the past, the first floor was converted into a store removing most of the partition walls. Furthermore, the internal load-bearing walls were weakened by at least two openings. In Fig. 5a the floor plan of the first floor in its condition during the vulnerability assessment is shown. The removed internal lateral walls are depicted with dashed lines. The almost identical upper stories have been used for housing purposes only. Figure 5b shows the floor plan of the second floor, representing exemplarily the upper floors. A section of this object is depicted in Fig. 5c. After the subsequently described assessment in 2009 the building was demolished.

4.1.2 Vulnerability assessment

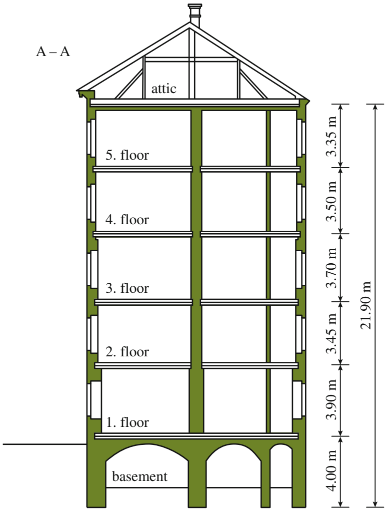
Subsequently, the evaluation of each parameter describing the Structural Parameter *SP* and the Damage Relevance *DR* of this building according to Tables 1, 2, 3, 4 is discussed. All individual parameters are summarized in Table 7.

Individual parameters of *SP*:

- Parameter S_{01} describing the seismic hazard is 2.0, because the building was located southwest of the river Danube, Table 1.
- The building was L-shaped, and thus its plane was irregular. Since the length to width ratio (23.68/21.44 = 1.10) is smaller than 4, according to Table 1 parameter S_{02} is 5.
- In the first floor almost all lateral partition walls have been removed, however, load bearing shear elements have been preserved. Thus, the regularity in elevation parameter S_{03} is 50, see Table 1.
- The steel ties connecting the timber ceilings and the walls were in bad condition throughout the building, thus leaving sub-parameter $S_{04,1} = 5.0$. Furthermore, the brick faults above the basement were also in bad condition, i.e. $S_{04,2} = 5.0$. According to Table 1 multiplication of $S_{04,1}$ and $S_{04,2}$ yields the horizontal stiffness parameter $S_{04} = 25.0$.



(a) 1. floor **(b)** 2. floor



(c)

Fig. 5 **a** Floor plan of the 1st floor, **b** floor plan of the 2nd floor, and **c** section of the object “Währinger Gürtel 164”

- Evaluation of parameter λ_0 according to D’Ayala and Speranza (2002) gives $\lambda_0 = 0.62$, which corresponds to failure of the object corner facing the intersection. Thus, parameter S_{05} evaluating local failure is 10, compare with Table 1.
- The building had seven chimneys (secondary structures), which were in bad condition. Since the building faced the major street “Währinger Gürtel”, the exposure to the public was high, i.e. parameter $S_{06} = 20.0$ (Table 1).
- The subsoil in the area of the building site is composed of layered deposits. The upper soil layer is made of young fluviatile sediments of about 5 m thickness, resting on quarternary sandy gravels of 10 to 15 m layer thickness. The third layer is an over-consolidated soil of tertiary clays, silts and sands (“Vienna clay”). According to EC8 this soil stratification

Table 7 Individual vulnerability parameters of the test object "Währinger Gürtel 164"

Structural parameters *SP* and damage relevance *DR*	Score
S_{01} Seismic hazard	2.0
S_{02} Regularity in plan	5.0
S_{03} Regularity in elevation	50.0
S_{04} Horizontal stiffness	25.0
S_{05} Local failure	10.0
S_{06} Secondary structures	20.0
S_{07} Soil condition	10.0
S_{08} Foundation	2.5
S_{09} State of preservation	26.3
Structural parameter (total score) $SP = \sum_{i=1}^{9} S_{0i}$	150.8
D_{01} Human exposure	50.0
D_{02} Public importance	1.0
D_{03} Economic importance	13.8
D_{04} Material assets	1.0
D_{05} Effects on the environment	10.0
Damage Relevance (total score) $DR = \sum_{i=1}^{5} D_i$	75.8

is classified into soil class E. Hence, according to Table 1 soil condition parameter S_{07} is 10.0.

- From rapid visual screening the type of foundation could not be identified, thus $S_{08} = 2.5$ (because the building is located in the 9th district, see Table 2).
- The building was not maintained for many years, and it was found in a neglected condition with very large extent of damage. Thus, according to Table 3 the basic score BS_{09} is 15.0. Both structural and non-structural elements exhibited major cracks distributed all over the object. The building was severely damaged due to ingress of water, i.e. factor $FS_{09} = 1.75$. The top ceiling was in a very bad condition, i.e. also this yields according to Table 3 the same factor $FS_{09} = 1.75$. Multiplication of the basic score BS_{09} with factor FS_{09} gives the parameter $S_{09} = 15.0 \times 1.75 = 26.25$.

The sum of these parameter yields the Structural Parameter *SP* = 150.8.

Individual parameters of *DR* according to Table 4:

- Based on the number of apartments and on observation of the number of customers in the stores the number of endangered individuals within the object was estimated to be 50. Thus, the human exposure parameter D_{01} is 50.
- Since this object was an ordinary residential building, parameter D_{02} is 1.
- The useable living area (ULA) of the building was 1277.5 m^2. During the visual inspection the potential price per m^2 was 1,801.9 Euro/m^2. The remaining life-time (RLT) was estimated to be 15 years. Evaluation of the benchmark equation according to Table 4 renders $D_{03} = 13.8$.
- The real assets at risk was low (residential building), thus $D_{04} = 1.0$.

Fig. 6 Map of the pilot area in the 20th district of Vienna. Inspected historic residential buildings highlighted

- The building faces the major street “Währinger Gürtel”, and thus, pedestrians were exposed to effects of (partial) building collapse. Thus, the corresponding parameter D_{05} is 10.

The sum of these parameter yields the Damage Relevance $DR = 75.8$.

According to Eq. (1) the object “Währinger Gürtel 164” belongs to the highest Vulnerability Class *VC*IV, because the Structural Parameter *SP* (=150.8) is larger than 140. Thus, this object was particular vulnerable to seismic excitation. Furthermore, according to the derived values for *SP* and *DR* it is categorized into Structural Class *SC*IV, Eq. (2), and into Relevance Class *RC*II, Eq. (3), respectively.

4.2 Large-scale investigation

4.2.1 Pilot area

The proposed RVS methodology was applied in a large-scale experimental investigation. Therefore, an adequate pilot area was chosen in the 20th district of Vienna including a set of 375 historic brick-masonry buildings. A site plan of the pilot area is shown in Fig. 6 with the inspected objects highlighted. It can be seen that the historic brick-masonry buildings are the predominant object type within the pilot area. In particular, whole blocks of buildings have remained homogenous since their construction in the nineteenth century. The survey of the buildings was performed continuously within a time period of three months.

4.2.2 Vulnerability assessment

In Fig. 7 the Damage Relevance *DR* is plotted against the Structural Parameter *SP* for each inspected building of this large-scale application. This figure reveals that the outcomes of the experiment show a precise separation of Vulnerability Classes *VC*III and *VC*IV either in

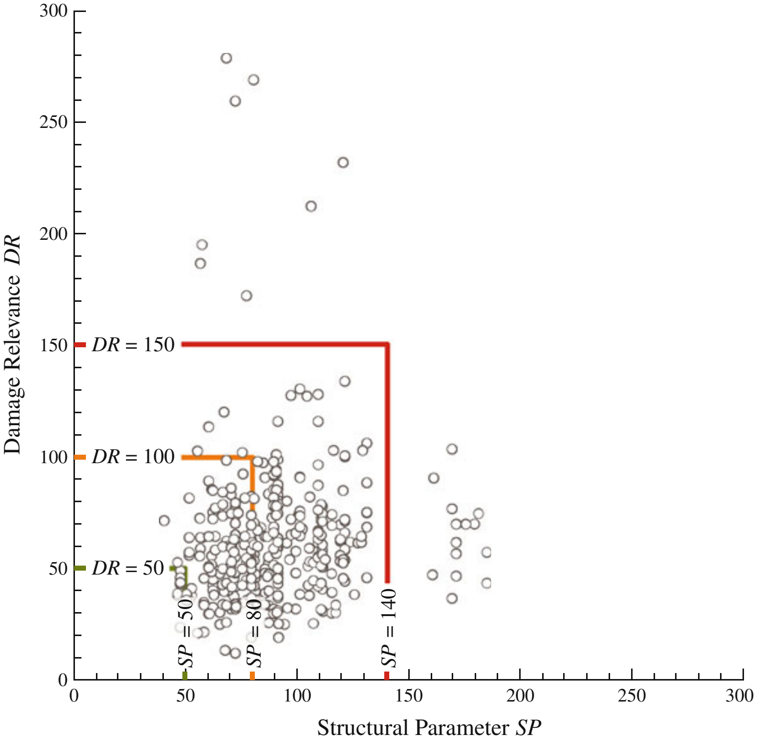


Fig. 7 Damage Relevance *DR* of various buildings plotted against the corresponding Structural Parameter *SP*. Pilot area in the 20th district of Vienna

terms of the Damage Relevance *DR* or the Structural Parameter *SP*. Hence, inspected objects classified into Vulnerability Class *VC*IV either have a comparatively high Damage Relevance *DR*, predominantly caused by the high number of exposed persons within the building, or have a very high Structural Parameter *SP*, which can be only generated by an irregularity in elevation. According to Fig. 7 most of the inspected objects were classified into Vulnerability Classes *VC*II or *VC*III without any precise separation between those classes. The main reason for that is the relatively large number of different individual parameters, which enter *DR* and *SP*, and hence, the benchmarks of a single parameter at a specific building may vary significantly.

Figure 8 shows the distribution of the damage relevance of the historic brick-masonry buildings located in the pilot area according to the classification of each object into a relevance class, Eq. (3). It is readily observed that particularly objects of high public interest, such as schools or public libraries, are classified into the highest Relevance Class *RC*IV because of the large number of exposed persons. The comprehensive results of each inspected building and any evaluated parameter can be found in Achs (2011).

4.2.3 Damage scenario

Based on the proposed correlation between the structural classes with predicted building damage, compare with Table 6, the Structural Parameter *SP* of each inspected object is

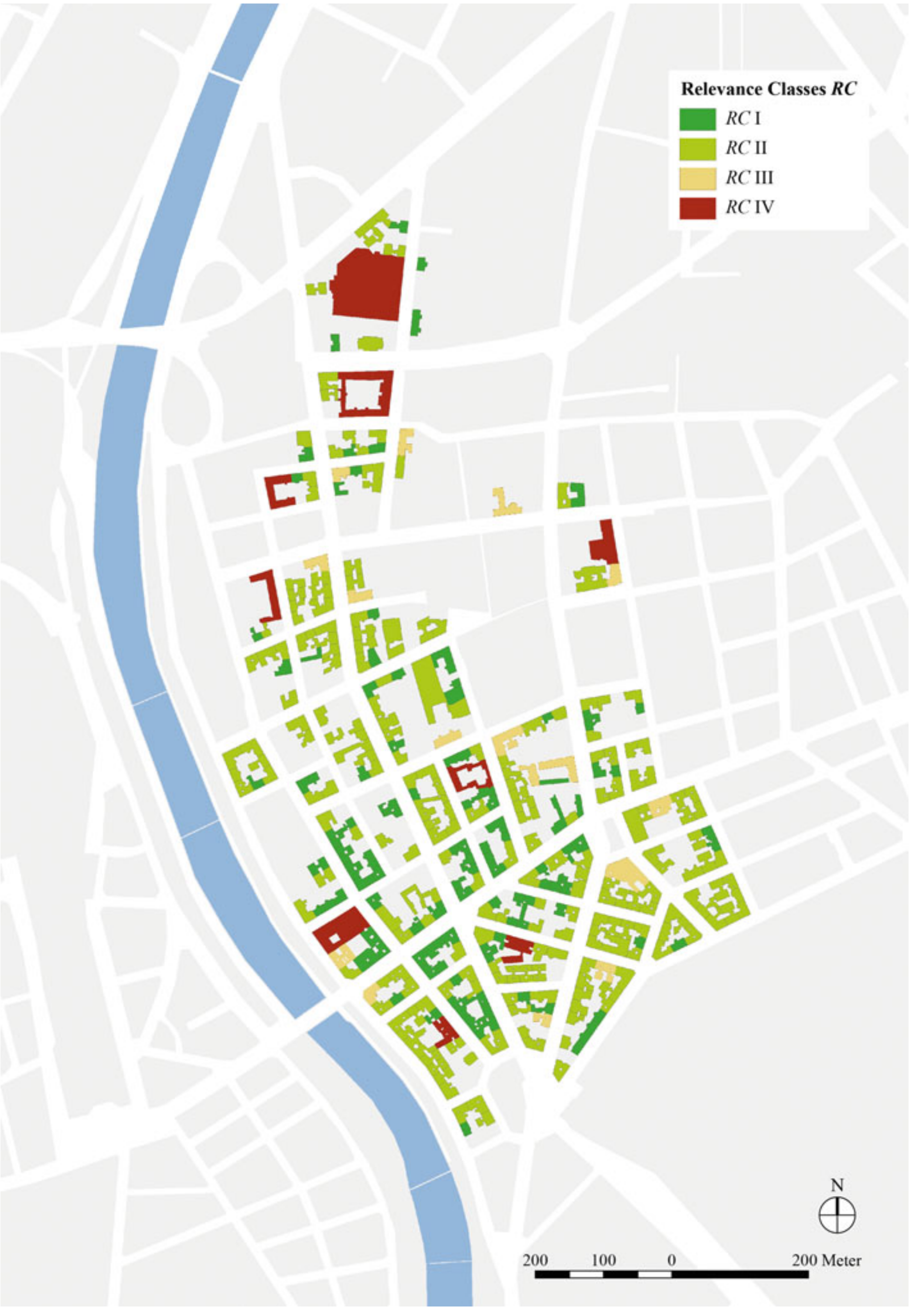


Fig. 8 Classification of the inspected objects in the pilot area into four relevance classes based on the Damage Relevance *DR*

transferred into a damage grade according to EMS-98. Figure 9 shows the number of objects as function of the corresponding Structural Parameter *SP*, and their classification into a Structural Class. When correlating the damage grades with the structural classes it should be

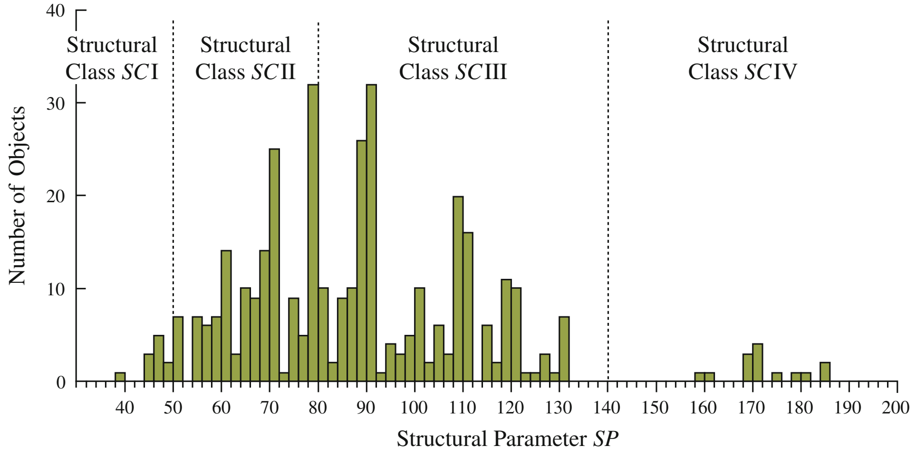


Fig. 9 Classification of the objects in the pilot area into four structural classes based on the Structural Parameter *SP*

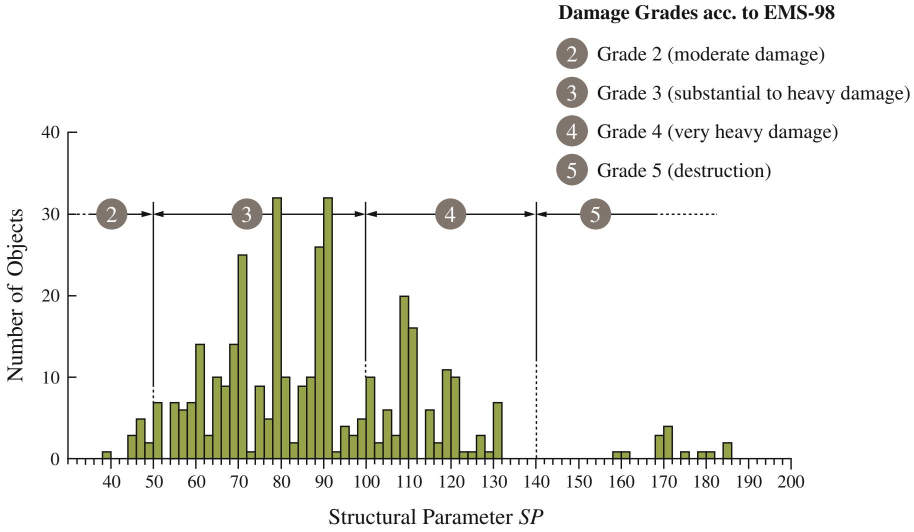


Fig. 10 Classification of the objects in the pilot area into five damage grades according to EMS-98 based on the Structural Parameter *SP*

considered that the separation of damage grades 3 and 4 does not strictly comply with the separation of Structural Classes *SC*II and *SC*III. For this particular study the selection of the threshold between Damage Grades 3 and 4 is based on a pragmatic “engineer’s approach”, as subsequently outlined. Inspection of Fig. 9 reveals that the number of objects in the range of *SP* between 92 and 108 is small, and separates the depicted distribution for Damage Grade 3 and 4 into two groups. Consequently, it is assumed that a Structural Parameter of $SP = 100$ (i.e. the mean of 92 and 108) separates Damage Grade 3 from Damage Grade 4, which is slightly above the assumed threshold between Classes *SC*II and *SC*III at $SP = 80$, compare Fig. 9 with Fig. 10. Furthermore, it should be taken into account that the direct correlation between structural classes and damage grades according to EMS-98 may be

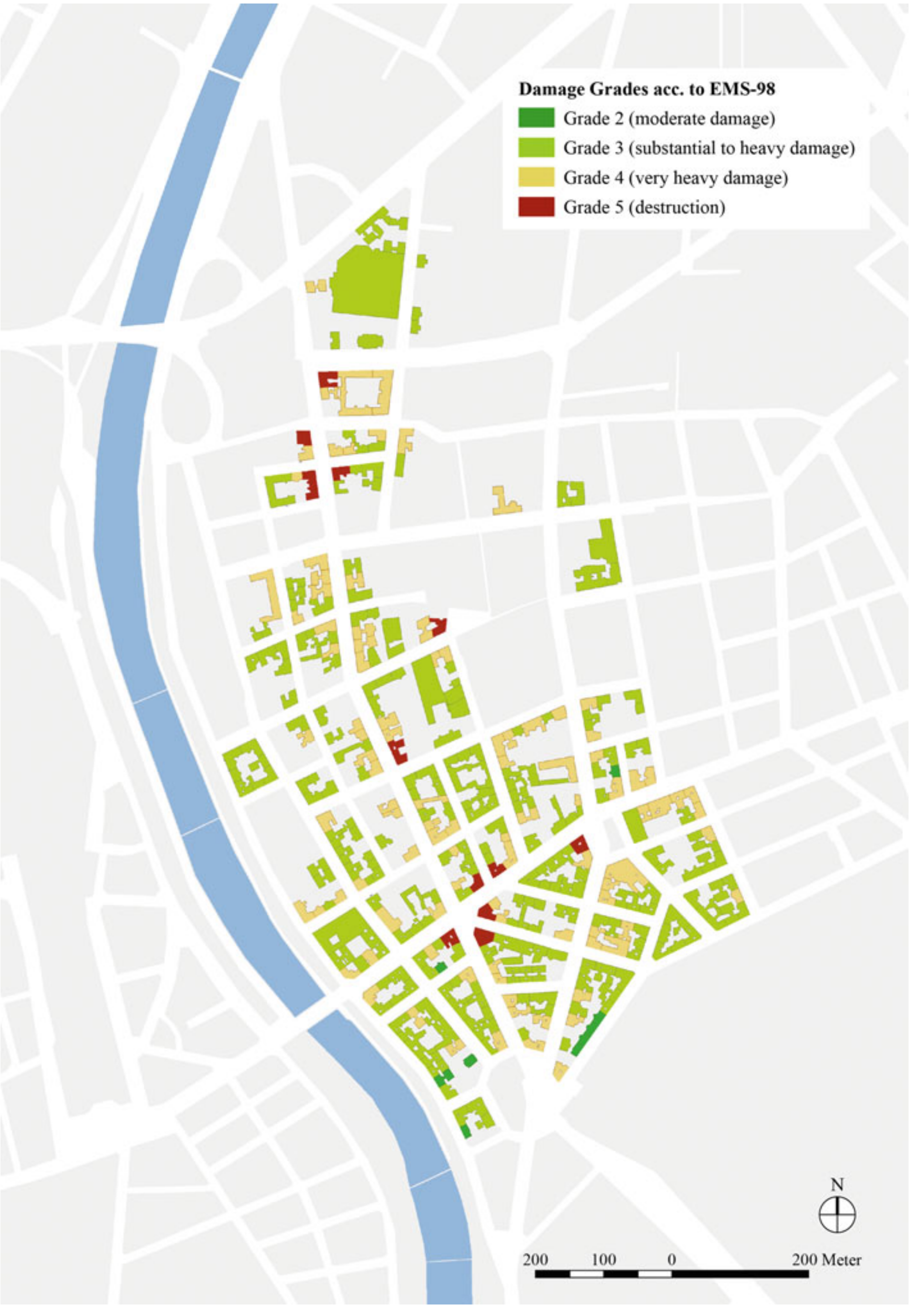


Fig. 11 Assessed damage grades according to EMS-98 of the inspected objects in the pilot area

problematic because the damage distribution of different buildings within a certain structural class may vary, as already shown in Table 6. Nevertheless the correlation of the results from the proposed RVS methodology with EMS-98 damage grades offers a comprehensive and rapid prediction of the possible impact of a certain earthquake with moment magnitude $M_w = 6.3$ on the inspected buildings. An illustrative presentation of the results from the investigated pilot area leads to the map of the predicted damage scenario shown in Fig. 11.

5 Conclusions

The RVS methodology is a fast and widespread method for seismic assessment of existing buildings. In this paper, a RVS methodology adopted for historic brick-masonry buildings in Vienna was presented. Those buildings represent the predominant type of constructions in the city center of Vienna, and so far there was no sufficient information available about their vulnerability against seismic action. The developed methodology consists of a visual inspection form and the subsequent evaluation of several parameters to capture the effects of possible damages on the environment and to describe and classify the structural behavior of the building under earthquake loading. Subsequently, the buildings are classified into four vulnerability classes to prioritize the building stock by using the evaluated parameters. Post-seismic damage observation on a similar building stock after the recent major L'Aquila 2009 earthquake event was used to correlate the results of the proposed RVS methodology with realistic seismic damage on masonry buildings predicting damage grades according to EMS-98.

The derived classification of the buildings may serve directly for earthquake-induced damage scenarios for Viennese urban areas with a large stock of historic brick-masonry buildings, or it may provide a basis for a more detailed investigation of objects identified to be potentially vulnerable against seismic action. Particularly, the evaluated maps of a predicted damage scenario may give useful information for rescue and safety planning in an emergency, such as selection of evacuation routes.

In a large-scale investigation a set of 375 historic brick-masonry buildings was evaluated by the proposed RVS methodology. The results of these tests were integrated into a local seismic building vulnerability map. The outcome of the proposed methodology supplies a good prediction of the damage distribution within the pilot area.

Acknowledgments The investigations described were performed within the Austrian research project SEISMID (Achs et al. 2011), which aimed, among others, at the development of a methodology to assess the actual seismic vulnerability of historic brick-masonry buildings located in Vienna. SEISMID was funded by the ZIT Center for Innovation and Technology, which is a subsidiary of the Vienna Business Agency (WWFF). This support is gratefully acknowledged.

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