Characteristics of buildings and seismic vulnerability assessment for the specific area of the city of Osijek

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Abstract. Seismic risk is a measure of the damage that is expected in a specific area and time interval. It is based on the level of seismicity of locations (hazard), the resistance of buildings (vulnerability), and the type, quality and quantity of exposed assets (exposure). It can be measured by the expected economic loss, loss of life or damage to property size. Reducing the seismic risk comprises three phases: assessment, planning and implementation. The risk assessment requires a multidisciplinary approach that takes into account the expected physical damage (damage to buildings and economic losses), as well as social, organizational and institutional factors. At the city level, a risk assessment should start assessing the physical damage as a result of basic tools and the link between risk and vulnerability values of buildings. In this paper the creation of a database of existing buildings, classification of buildings and a procedure for determining the building typology that prevail in the city of Osijek is described. Based on the formed database, it is possible to implement certain seismic vulnerability methods.

1. Buildings database for the city of Osijek

An initial step in assessing the vulnerability of all types of buildings potentially exposed to earthquakes is creating a database of buildings.

Although building databases are extremely important, data collection for them is rarely part of the established collection processes for data of interest to society [1].

The assessment of the exposure of and damage to buildings in the Republic of Croatia is aggravated by the fact that there is no city that has a database with information on the number, types and characteristics of existing buildings.

That is why, at the Faculty of Civil Engineering and Architecture in Osijek, a project of creation of the database of buildings for the city of Osijek has been started. The goal of this project is to produce reliable and useful information on attributes that describe the structural and other characteristics of city buildings, and which will satisfy the needs for accurate and high-quality earthquake and other risk assessments for the city of Osijek.

Building database also provides data needed for quantifying damage in monetary units [2].

A high-quality building database for a particular area of research implies, first and foremost, the availability of complete and detailed information on the geographical location of buildings, their total surface area and their structural characteristics. However, due to common problems such as...
inaccessibility or lack of official data and statistics to assign relevant characteristics and parameters, approximate procedures are often used.

The process of creating a database requires the collaboration of numerous experts in various fields of science as well as civil engineering practitioners. Gathering all the necessary building data requires finding and analyzing building documentation, field visual data collection and measurements, and the final analysis and documentation of the collected data.

Numerous methods have been developed to estimate earthquake exposure and damage to buildings. The reliability and precision of these methods depends on the classification of the buildings, which must cover all the individual features of the buildings in a uniform manner.

Although the use of the already developed classifications (PAGER-STR, HAZUS, GEM, etc.) is common, their use in geographic environments for which they have not been developed may cause epistemic uncertainties in a later vulnerability model [3].

That is why the building database for the city of Osijek, at the building level only certain, valuable attributes are being collected, as the most likely related to certain existing building typologies in the city and which allow for risk calculation for each investigated building according to its compatibility in relation to one or more construction.

The building database of the city of Osijek contains more than 1000 buildings so far and continues to be completed and upgraded.

2. Structural systems Classification

By identifying the recurring characteristics, and analyzing similarities and changes in the structural features of existing buildings in the city of Osijek, the structural systems of the existing buildings in Osijek are classified as follows:

- M5 – unreinforced masonry structures with flexible floors (old bricks),
- M6 – unreinforced masonry structures with rigid floors,
- M7 – masonry structures with horizontal and vertical ties (confined masonry),
- RC1 – reinforced concrete frames,
- RC4 – shear walls (without E.R.D.).

In adopting the classification, guidelines and designations from Giovinazzi [4] were respected and used.

The years when buildings were built and the basic structural and performance requirements in building regulations at the time when they were built, were the basic criteria we used to classify buildings into adopted classes. For the buildings in the current database, figure 1 shows percentages of certain structural system classes.

The data shown in figure 1 indicate that 98% of the buildings that are so far included in the Osijek's building database, are masonry structures.

The significant percentage of masonry in the city and the complex and extremely nonlinear behavior of masonry during the earthquake justify the creation and existence of this database and reduce the fact that relatively few low intensity earthquakes have been recorded in the city and the surrounding area. The database represents the basis for reliable assessment of the earthquake vulnerability for all types of buildings in the city, and hence for the reliable assessment of seismic risk [5].
A series of seismic microzonation studies made for the north-western Balkans [6-10] and a recent study of strong earthquake ground motion in the same region [11], all show that deep geological sediments strongly affect the severity of both longer period waves. The Osijek is located in the valley, near the river Drava, and the deep geological deposits beneath it are comprised of the rocky, sandy and muddy soils with infrequently high groundwater levels. These deposits can be significantly disturbed by distant earthquakes and cause damage to the housing stock, especially to masonry buildings.

3. Features that describe the buildings in the database

The earthquake resistance of a building is influenced by some characteristics more than others, e.g. the lateral resistance of the structure and the predominant material by which the structure is built (brick, reinforced concrete, steel, etc.). Therefore, selecting the relevant parameters that will best describe the construction and other features of the building is the initial step in the process of creating a building database.

The Global Earthquake Model (GEM Basic Building Taxonomy v2.0) recommends 13 building characteristics that, alone or in synergy, can significantly affect the behavior of buildings during an earthquake [12]. However, in reality it is almost impossible to identify all of those characteristics.

When selecting the characteristics that will describe the existing buildings of the city of Osijek, the recommendations from the GEM were taken into account, but their number was reduced due to the lack of availability of some of them, and their selection was adjusted to the specific characteristics of the construction technology and materials from which the existing buildings in the city were built.

A form was created for the field data collection, and a mobile application was later developed to collect the following building data:

- building location information: address, cadastral number,
- the position of the building in relation to the particular city block,
- general information: the purpose of the building, the year of construction and/or reconstruction, (if any), and the number of persons living in the household,
- information on the geometric characteristics of the building: floor plan dimensions, net and gross floor planes, floor plan blueprints, floor level, floor space, and total height,
- regularity in floor plan and height,
- information on the main structural system of the building,
- information on building materials used,
- information on the roof structure and cover.
According to Salgado-Galvez et al. [13], the characteristic that can significantly influence potential earthquake damage to buildings is the age of the structure. In addition, this characteristic can be used to determine the used design codes and to define the type of load-bearing structures.

Given the characteristic construction technologies, the time periods during which buildings from the city of Osijek database were constructed are divided into 4 groups – see figure 2.

![Figure 2. The proportion of buildings in the current database for the city of Osijek with respect to year of construction.](image)

The data collected so far on the year of construction of the buildings in the database show that the largest number of buildings was built between 1970 and 1987, and the smallest number of buildings in the period prior to 1940.

Among the most critical features in terms of the expected earthquake behavior of buildings are structural irregularities (floor plans and/or verticals).

González Herrera and Gómez Soberón [14] studied the devastating earthquakes of 1980-2003 and their impact on residential buildings. Their research has shown a great cause and effect relationship between the degree of damage to a building (due to an earthquake) and structural irregularities in the affected buildings.

Eurocode 8 [15] also stipulates that the structural system of buildings must be approximately symmetrical with respect to the two orthogonal axes to ensure sufficient lateral rigidity and proper mass distribution. In addition, the building must have a compact configuration plan and the corners or edges of the entrance, if any, should not exceed 5% of the floor area.

The buildings covered by the database are mostly rectangular. With respect to the regularity of the ground plan, 75% of buildings have the regular floor plan and 25% have the irregular floor plan, as shown in figure 3.

An important characteristic for damage modeling is the position of the buildings in the city block. Specifically, in densely populated urban centers, buildings are at risk of impacting each other, and more damage can be expected on buildings located at the end of a series of buildings and at corners.

The fundamental period of vibration can have a significant impact on the behavior of a building during an earthquake. The height of the building is one of the characteristics that determines this dynamic property.

Higher buildings are characterized by longer vibration periods and are usually considered flexible; however, this does not mean that they will suffer less damage than low or lighter buildings.
In addition to determining the earthquake hazard, the earthquake behavior of high and low buildings is also influenced by the characteristics of the underlying soil, and not only by the first 30 m of the soil profile, but also by the deep geological layers [11].

Numerous modern reinforced concrete high rise buildings were destroyed in the 1985 Mexico City earthquake due to amplified vibration in soft soil deposits and because of the resonance caused by a predominant shaking frequency of about 2 sec.

Most of the buildings listed so far in the Osijek building database are lower buildings, generally up to 4 stories high.

Good earthquake transmission during earthquake action is ensured by the floor system that is sufficiently rigid in its plane. The floor system must prevent the walls from being separated and ensure that during an earthquake, the building acts as a single spatial structure with well-connected elements. Softer floors (i.e. wooden floors) often cannot be considered absolutely solid in their plane, so the transmission of earthquake forces onto all vertical elements is not entirely ensured.

In the city of Osijek database, floor systems are classified as rigid or wooden floor systems, and their percentage distribution in the current database is shown in figure 4.

The parameter that has a strong influence both on the behavior of the structural elements and on the entire structure during earthquakes is the construction material or the type of building material from which the building was made. Buildings that are completely identical in terms of floor planes, number of floors, structural type, etc., but made of different types of materials, will have significantly different
behavior even for the same intensity of earthquake ground shaking. The worst earthquake behavior can be expected in the case of unreinforced masonry and reinforced concrete frames with masonry fill, while reinforced concrete buildings with shear walls, steel frame buildings and wood buildings can be expected to show very good performance during the same earthquake.

For the city of Osijek database purposes, the construction material data are collected on site, from project documentation, based on knowledge of the building users or by evaluation based on knowledge of building age and researcher’s experience.

The walls of the base building are made of brick and/or concrete. Using a brick block is the most common: 922 buildings, or 86%, were built by brick blocks. The ordinary (most commonly used) brick was used in 128 buildings, which is 12% of the total number of buildings. Concrete walls were used in 15 buildings or 1%, and concrete blocks in 5 buildings or 0.5% of the total number of buildings. In the database there were also 5 masonry buildings which were constructed of raw brick (in Tvrđa and Upper Town), and that makes 0.5% of all buildings (figure 5).

The walls of the building from the Osijek base are mostly made of brick elements – see figure 5. The most commonly used are brick blocks in 86% of buildings and ordinary brick in 12% of buildings. In the oldest parts of the city (in Tvrđa and Upper Town), the walls of the building are made of adobe.

![Figure 5. The proportion of buildings in the current database for the city of Osijek with respect to wall materials.](image)

The data on buildings collected so far shows that the average gross floor area is 769 m² and the average floor area is 226 m². The total height of the buildings is between 4.48 m and 37.3 m, and the average height is 8.46 m. These data are shown in figure 6.

![Figure 6. The proportion of buildings in the current database for the city of Osijek with respect to average dimensions.](image)
So far, the data have been collected for buildings in the following city areas: Tvrđa, larger parts of the Upper Town, New Town (Sjenjak), some parts of the Industrial District, Retfala and South II, and the current database currently covers at least the whole Lower Town area – see figure 7.

4. Seismic vulnerability assessment for the selected city block

4.1. Characteristics of the buildings from the selected city block

In this article, a seismic vulnerability assessment is applied for the selected city block. The observed area includes 69 buildings in the wider city center of Osijek (figure 8), of which: 47 are residential buildings, 14 residential/commercial buildings and 7 commercial buildings. The necessary data on the buildings were collected by field work, searching on the Internet and visiting the State Archives of the City of Osijek.

Most of the buildings are single-storey buildings with wooden floors, and their structural system is a masonry structure. The buildings are old, built with a traditional approach, while bricks are used as the main building material. Figure 9 shows an example of a typical unreinforced masonry building with a flexible floor structure.
Figure 9. Typical building from the city block analysed in this study.

It can be seen from figure 10 that in this city block, 96% of the buildings are unreinforced masonry buildings with wooden floors (M5), 3% are unreinforced masonry buildings with rigid floors (M6), while only 1% is confined masonry (M7).

Figure 10. Structural system of the buildings in the city block that is analyzed in this study.

4.2. Macro seismic method

Macro seismic method, developed by Giovinazzi and Lagomarsino [4], [16] from the definition provided by the European Macro seismic scale EMS-98 [17], is also called “indirect” since the relationship between seismic action and the response is obtained through the vulnerability index. Vulnerability is measured in terms of a vulnerability index $V_I$ and a ductility index $Q$, both evaluated considering the building typology and its constructive features [16].

The correlation between the seismic input and the expected damage, as a function of the assessed vulnerability, is expressed in terms of vulnerability curves described by a closed analytical function [16]:

$$\mu_D = 2.5 \left[ 1 + \tanh \left( \frac{I + 6.25 \times V_I - 13.1}{Q} \right) \right],$$

where:

$I$ – the macroseismic intensity;
$V_I$ – the vulnerability index;
$Q$ – the ductility index; the proposed value is 2.3 for residential buildings.

The vulnerability index $V_I$ of every building considers the regional vulnerability modifier and the behavior modifier. The behaviour modifiers take into account the following characteristics of each building:
- building irregularities,
- number of floors,
- vertical irregularity,
- state of preservation,
- aggregate building position etc.

The total behavior modifier for a single building is the sum of the individual values. The calculated vulnerability index for every building can be connected with most probable damage state (table 1).

### Table 1. Damage states and mean damage index values [18]

| Mean damage index intervals | Most probable damage state       | EMS-98 Damage Grade |
|-----------------------------|---------------------------------|---------------------|
| 0-0.5                       | None                            | D0                  |
| 0.5-1.5                     | Slight                          | D1 (Grade 1)        |
| 1.5-2.5                     | Moderate                        | D2 (Grade 2)        |
| 2.5-3.5                     | Substantial to heavy            | D3 (Grade 3)        |
| 3.5-4.5                     | Very heavy                      | D4 (Grade 4)        |
| 4.5-5.0                     | Destruction                     | D5 (Grade 5)        |

The calculated vulnerability indices for the buildings of the selected city block, connected with most probable damage state, are presented in figure 11 for two levels of intensity, VIII and IX.

![Figure 11](image-url)

**Figure 11.** Most probable damage states obtained for intensities: a) VIII, b) IX, for the city block that is analyzed in this study – the same colors that are used in table 1 are used here to indicate different damage states.
5. Conclusions
Seismic vulnerability assessment, as a main component of earthquake risk, can only be performed if there is exposure, i.e. a database of buildings. In this paper, the characteristics of the buildings database of the city Osijek is presented, which, so far, contains more than 1,000 buildings. The dominant structural systems, that is, the typology of buildings, the characteristics of the buildings in the data base are also shown: number of floors, planar and vertical regularity, position in the block, year of construction, etc. are collected. The collected data on buildings, visual inspection, and the available documentation in the National Archives are classified in the database and analyzed. The purpose of the database is to enable an assessment of the seismic vulnerability for the existing city buildings.

In the example of the selected Osijek city block, the goal was to assess seismic vulnerability. Therefore, the vulnerability was conducted and estimated for the several blocks of the city Osijek by an empirical earthquake vulnerability estimation method, the macroseismic method. The macroseismic method calculates a vulnerability index, which is a function of the most likely value of an index of damage of a type of building, a regional and a behaviour modifier. The influence of the behavior modifier is expressed in the increase in the vulnerability index. Based on the calculated vulnerability indices, the mean damage grade of each building was calculated for two levels of seismic intensity. The mean damage grade can be correlated with the most likely damage state according to EMS-98. According to the obtained results, the calculation of the macroseismic method show that the unreinforced masonry structures with wooden floors for earthquake of intensity VIII will suffer moderate damages (most likely damage state), and for earthquake of intensity IX those buildings will suffer substantial to heavy damages. Due to similarities in existing building types, these conclusions can be extended in other regions of Croatia, especially in northern and eastern parts of the country.

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