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Original article

Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index

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ABSTRACT

Osijek is the largest city in eastern Croatia and the fourth largest city in the country. The most preserved Baroque buildings of Croatia are located in Tvrdja, the old historical city core. Tvrdja represents the educational, cultural and administrative centre of Osijek, and consists of 106 buildings. One of the problems facing civil engineers today is preserving a large number of older masonry buildings, built in areas of seismic active zones. It is very important to evaluate the existing earthquake resistance of these buildings in order to strengthen existing buildings and/or prepare emergency plans using realistic seismic scenarios. Therefore, it is desirable to provide a relatively fast but accurate seismic vulnerability assessment, which the proposed method in this paper satisfies. The aim of the article is to determine, using Damage Index coefficient, the seismic vulnerability of a historical building located in Tvrdja. For the analysed area, a set of seven earthquake records is specified, and using different structures modelled as single-degree-of-freedom systems, Damage index spectral functions are determined. Thus, by knowing the proposed parameters of a single-degree-of-freedom system representing an unreinforced masonry building, a response of the structure to a given earthquake can be determined using the graph of Damage index spectral functions.

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1. Research aim

The main aim of the article is to determine the seismic vulnerability of a historical building located in Tvrdja. The damage of a structure and its elements can be defined as a certain degradation of the building due to its structural features caused by the action of seismic load of a specific intensity. The extent of damage to a structure can be expressed with Damage index (DI), which is given by the formula in [1,2]. The aim of this work is to adapt the DI formula proposed in [2,3] for masonry structures, and implement it to determine the seismic vulnerability of a selected historical building located in Tvrdja.

The proposed, modified, assessment method is a non-destructive and relatively fast, but accurate seismic vulnerability assessment procedure. Thus, it may be used to evaluate the existing earthquake resistance of the buildings in the old city core of Tvrdja in order to strengthen existing buildings and/or prepare emergency plans. Similarly, by suitably modifying the proposed method for other structures, the vulnerability assessment procedure of other

cultural heritage located in seismic areas may be simplified and expedited.

2. Introduction

The initial stage of protecting a city from an earthquake disaster is to form and possess a theoretical forecast of the aftermath: structural damage and/or socio-economic losses that may occur after an earthquake. This forecast is obtained by performing seismic vulnerability assessment. The selection of a suitable method for seismic vulnerability assessment depends on the objective and nature of the study, decision makers, characteristics of the (group of) buildings under study, available information and organization of data collection [4]. The methods can be qualitative or quantitative (e.g. empirical or analytical). Qualitative methods assess the seismic vulnerability of a large group of buildings and provide a qualification in terms that could range from low to high [5]. Empirical methods are based on observing damage suffered during past seismic events. An evaluation of damage probability matrices (DPMs) from observed seismic damage data for typical structural types and compared to existing matrices derived from regions with similar building stock and soil conditions was conducted in [6].

Compared to qualitative methods, quantitative methods thoroughly evaluate a given building and provide the vulnerability in

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numerical terms (e.g. displacement capacity, ultimate force etc.). For example, in [6], performance based assessment of 16 reinforced concrete (RC) buildings in Bitlis was carried out. Structural performance was ascertained by applying the nonlinear methods provided in the latest Turkish Earthquake Code published in 2007 [7]. The results indicated that 13% of the buildings were determined as having Life Safety performance level, with 53% of them in the Fully Operational performance level. The vulnerability of confined masonry building was analytically evaluated in [8]. In the aforementioned paper, nonlinear dynamic analysis was performed on a six-story masonry building built in 1957, typical for the considered area and designed without any seismic guidelines. Seismic performance of modern 44 stories rc shear walls (SW) high-rise building was presented in [9].

Vulnerability assessment of cultural heritage located in seismic areas has been actively researched of late. Since such buildings are anisotropic, highly diverse, have complex geometry and heavy masonry mass, this complicates seismic analysis [10]. Most of the attention is paid to the modelling of individual buildings and assessment methods based on non-destructive procedures or micro destructive testing as well as dynamic identification process in order to determine the modal shapes, frequency and damping coefficient through ambient vibrations [11–13]. Hence, the vulnerability assessment procedure of a historical building is much more detailed and requires more computer resources and special equipments compared to empirical methods. Perhaps a key for the rapid assessment of these buildings lies in a hybrid approach, whereby experimental and analytical methods are combined in order to obtain quantitative and more reliable results for the group of buildings.

It is known that Croatia is located in a seismically active zone, as evidenced by a series of catastrophic earthquakes that affected it throughout its history. Croatian territory is part of the Mediterranean zone of the Alpine-Himalayan seismic belt and comprises several distinct geotectonic units: the Dinarides, the Eastern Alps, the Pannonian Basin, the Adriatic Platform and the transition zone between the Dinarides and the Adriatic Platform. [14]. The seismicity of Croatia is described using the Croatian Earthquake Catalog [15], which is updated yearly. The seismic hazard for Croatia is presented using two maps [16], which are part of the National Annex to EN 1998-1 [17]. Hazard is expressed in terms of the maximum horizontal ground acceleration which is, on average, exceeded once in 95 or 475 years.

A significant number of old buildings, which are built from stone and masonry blocks, are not following any provision and they are not in accordance with earthquake-resistant design. It is necessary to evaluate the level of risk for these old buildings.

As of 2011, Osijek has 108,048 inhabitants, and is the largest city of the Osijek-Baranja County. It is also the fourth largest city in Croatia. It represents the administrative, economic, and cultural centre of the Osijek-Baranja County. Osijek is located about 25 km upstream of the confluence of the rivers Drava and Danube and is on the right bank of the river Drava. The old city core of Osijek is Tvrdja. It is an eighteenth-century complex of cobbled streets, grand buildings and open squares and is the most conserved set of Baroque buildings anywhere in Croatia. The World Monuments Fund describes Tvrdja as “a unique example of an eighteenth-century baroque military, administrative, and commercial urban centre”. With its 106 buildings, which were originally residential houses and army barracks, Tvrdja is now the centre of Osijek in terms of scholarly life, education, culture and administration.

Currently, no seismic vulnerability assessment has been performed for Tvrdja, nor systematically for Osijek. This work is a contribution in this direction.

3. Study area

Tvrdja is a unique example of 18th century fortification architecture of the Austrian empire as well as one of the most valuable Baroque units in Croatia. Apart from a few abandoned houses, there are about a hundred family houses, schools, public buildings, churches and restaurants. The majority of the buildings in Tvrdja have not retained their original purpose.

The construction of Tvrdja officially began in 1712, and was supervised by General Johann Stephen von Beckers, who was the city and fort's commander. When completed around the mid-18th century, it consisted of eight bastions, located from east to west around the town, a protective wall and a moat as well as protective fortresses on the outside. Blocks of town houses, monasteries, public and military buildings were surrounded by seven barracks and powder magazines. Four main gates were built on each side of the fort (east, west, north and south) as well. Only a few new objects were built inside the fortress during the 19th century.

All the buildings within the fortress could be built only with the permission and under the direction of the military administration. The most important conditions were: obligatory construction of houses with solid material or fired bricks, tiled roof and masonry chimney. The basements of the buildings were built with strong foundation walls and have barrel vaulted ceilings. In the basements, the bricks are often unconcealed with the stacking visible. Single storey buildings are not arched, while multistorey buildings usually have a barrel vault. The floors are made of brick, timber or small stone slabs and staircases are usually made of timber. The ceilings of the first floor are made of oak beams, and in accordance with fire regulations were sprinkled with sand and paved with bricks. All the buildings are plastered.

Although most of the outer fortifications have long since been demolished, the very heart of this complex still exists in its original form (Fig. 1a). The standard star-shaped fortress concept has been modified in accordance with the existing urban structures and is based on the flow of the river. Its 106 structures – originally residential houses and army barracks – make this complex a unique example of fortification of the baroque age in Croatia. Due to a century of long economic decline, several population exoduses and serious war damages (1991–1992), a once dominant and prosperous heart of the city became an unpopular and neglected neighbourhood. 90 per cent of the buildings in Tvrdja were more or less damaged.

Tvrdja is now the educational, cultural and administrative centre of Osijek – the rectorate and various departments of the Josip Juraj Strossmayer University of Osijek are located there (Fig. 1b). Other present-day educational institutions in Tvrdja include several secondary schools (Figs. 1c and d). Other institutions include the National Archives, the Conservation Department of the Ministry of Culture, etc.

4. Seismic vulnerability assessment method

Preciado et al. [5] proposed the following categories for vulnerability assessment methods: empirical or qualitative; analytical or quantitative; hybrid methods, depending on whether the sources of damage information are derived from post-earthquake surveys; analytical simulations, or a combination of these, respectively. Empirical assessment methods are based on the observation of damage suffered during past seismic events. The main types of empirical methods are Damage Probability Matrices, Vulnerability Index Method and Screening Methods. Some of these methods have been implemented in many researches [18,19]. Analytical methods are used when a single building is evaluated in a detailed way and in numerical terms (displacement capacity, ultimate force

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