Scientific reports on open access journals and on the project web site

Final Version of 30/06/2022

Deliverable Number D.3.3.5.

Project Acronym	PMO-GATE
Project ID Number	10046122
Project Title	Preventing, Managing and Overcoming natural-hazards risk to mitiGATE economic and social impact
Priority Axis	2: Safety and Resilience
Specific objective	2.2: Increase the safety of the Programme area from natural and man-made disaster
Work Package Number	3
Work Package Title	Assessment of single-Hazard exposure in coastal and urban areas
Activity Number	3
Activity Title	Assessment of climate-unrelated hazards exposure in urban and coastal areas (seismic action)
Partner in Charge	UNIVERSITY OF SPLIT, FACULTY OF CIVIL ENGINEERING, ARCHITECTURE AND GEODESY
Partners involved	UNIVERSITY OF SPLIT, FACULTY OF CIVIL ENGINEERING, ARCHITECTURE AND GEODESY UNIVERSITY OF FERRARA, DEPARTMENT OF ENGINEERING
Status	Final
Distribution	Public

Summary

Abstract

A methodology for seismic vulnerability and risk assessment of historical urban area typical for east side of Adriatic coast and its application to the Croatian settlement of Kaštel Kambelovac chosen as HR test site have been presented in two articles published in open access journal “Applied sciences”. In addition, during the project the activity 3.3 “Assessment of climate-unrelated hazards exposure in urban and coastal areas (seismic action)” has been presented at several conferences. All papers have been made in cooperation between the project partner UNIST-FGAG and lead partner UNIFE. They are available at the project web-site.

1 Scientific reports on open access journals

1.1 Article “Seismic Vulnerability Assessment of Historical Masonry Buildings in Croatian Coastal Area“

An article “Seismic Vulnerability Assessment of Historical Masonry Buildings in Croatian Coastal Area“ [1], has been published in open access journal “Applied sciences” in June 2021. This article presents scientific report of the developed methodology for the assessment of seismic vulnerability and damage of a limited number of stone masonry buildings in the historical core of Kaštel Kambelovac.

The article highlights an importance of the protection of built heritage in historic cities located in seismically active areas for the safety of inhabitants. Systematic care and planning are necessary to detect the seismic vulnerability of buildings, in order to determine priorities in rehabilitation projects and to continuously provide funds for the reconstruction of the buildings. The seismic vulnerability of the buildings in the historic center of Kaštel Kambelovac, a Croatian test site located along the Adriatic coast, has been assessed through an approach based on the calculation of vulnerability indexes. The center consists of stone masonry buildings built between the 15th and 19th centuries. The seismic vulnerability method was derived from the Italian GNDT approach, with some modifications resulting from the specificity of the buildings in the investigated area. A new damage–vulnerability–peak ground acceleration relation was developed using the vulnerability indexes and the yield and collapse accelerations of buildings obtained through non-linear static analysis. Results of the investigations, represented with a seismic vulnerability map, critical peak ground accelerations for early damage and collapse states, and damage index maps for two return periods, have been predicted using the developed damage curves. The article concludes that the methodology developed in the PMO-GATE project, which combines the vulnerability index method with non-linear pushover analysis is an effective tool for assessing the damage of a building stock on a territorial scale.

The first page of the article is shown in Fig. 1. The article is available at the web-site of open access journal “Applied sciences” (Link: https://www.mdpi.com/2076-3417/11/13/5997, file:///C:/Users/gf-nikolic/Downloads/applsci-11-05997-v2.pdf).

applied sciences
MDPI

Article

Seismic Vulnerability Assessment of Historical Masonry Buildings in Croatian Coastal Area

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Abstract: (1) Background: The protection of built heritage in historic cities located in seismically active areas is of great importance for the safety of inhabitants. Systematic care and planning are necessary to detect the seismic vulnerability of buildings, in order to determine priorities in rehabilitation projects and to continuously provide funds for the reconstruction of the buildings. (2) Methods: In this study, the seismic vulnerability of the buildings in the historic center of Kaštel Kambelovac, a Croatian settlement located along the Adriatic coast, has been assessed through an approach based on the calculation of vulnerability indexes. The center consists of stone masonry buildings built between the 15th and 19th centuries. The seismic vulnerability method was derived from the Italian GNDT approach, with some modifications resulting from the specificity of the buildings in the investigated area. A new damage–vulnerability–peak ground acceleration relation was developed using the vulnerability indexes and the yield and collapse accelerations of buildings obtained through non-linear static analysis. (3) Results: A seismic vulnerability map, critical peak ground accelerations for early damage and collapse states, and damage index maps for two return periods have been predicted using the developed damage curves. (4) Conclusions: The combination of the vulnerability index method with non-linear pushover analysis is an effective tool for assessing the damage of a building stock on a territorial scale.

Keywords: seismic vulnerability; historical masonry buildings; vulnerability index; pushover analysis; damage index; large-scale assessment

Citation: Nikolić, Ž.; Runjić, L.; Ostojić Škomrlj, N.; Benvenuti, E. Seismic Vulnerability Assessment of Historical Masonry Buildings in Croatian Coastal Area. *Appl. Sci.* **2021**, *11*, 5997. https://doi.org/10.3390/app11135997

Academic Editor: Marco Vona

Received: 21 May 2021
Accepted: 23 June 2021
Published: 28 June 2021

1. Introduction

Many countries with moderate to high seismic risks, including Croatia, have old towns with stone or brick masonry buildings, built long before the approval of the first seismic regulations. Some of these towns are categorized as cultural heritage sites and should be preserved for future generations. Strong earthquakes cause significant damage and failure of such buildings. Rehabilitation requires significant financial resources that cannot be allocated suddenly. Therefore, systematic care and planning are necessary to detect the seismic vulnerability of buildings, in order to determine priorities in regard to their rehabilitation and allocate funds for reconstruction.

Evaluating the seismic vulnerability and capacity, as well as the damage state, is a demanding task even for a single building. It requires complex non-linear methods such as nonlinear static (pushover) analyses [1,2], in which the structure is gradually loaded according to a uniform or a modal pattern up to the point of collapse, or incremental dynamic analyses [3], in which ground acceleration is increased up to the point of structural collapse. Both types of analysis allow the determination of the collapse load as well as the monitoring of the damage level, which is continuously increasing because of the nonlinear dissipative processes, including the fracturing and plasticity of the structural components. Due to the restrictions of the non-linear static analysis for structures that

Fig. 1. The first page of article

1.2 Article “Seismic Risk Assessment of Urban Areas by a Hybrid Empirical-Analytical Procedure Based on Peak Ground Acceleration “

An article “Seismic Risk Assessment of Urban Areas by a Hybrid Empirical-Analytical Procedure Based on Peak Ground Acceleration“ [2], has been published in Special issue “Natural-Hazards Risk Assessment for Disaster Mitigation” of open access journal “Applied sciences” in June 2022. Organizers of this special issue are researchers of PMO-GATE project from University of Split and University of Ferrara.

This article fully extends the scale of the settlement and properly upgrades a methodology previously proposed by authors to predict seismic damage and the risk to a restricted number of masonry buildings in the Croatian settlement Kaštel Kambelovac located along the Adriatic coast. The proposed approach is based on a hybrid empirical-analytical procedure that combines seismic vulnerability indices with critical peak ground accelerations for different limit states computed through a non-linear pushover analysis. The procedure’s outcomes are the computation of a relationship linking vulnerability indices to peak ground acceleration for a series of states, corresponding to damage limitation, significant damage, and near collapse. The described methodology is used to estimate seismic risk in terms of damage and the index of seismic risk for selected return periods. The general methodology has allowed a full seismic vulnerability assessment of the whole Croatian settlement of Kaštel Kambelovac.

The first page of the article is shown in Fig. 2. The article is available at the web-site of open access journal “Applied sciences” (Link: https://www.mdpi.com/2076-3417/12/7/3585, file: https://www.mdpi.com/2076-3417/12/7/3585/htm).

applied sciences
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Article

Seismic Risk Assessment of Urban Areas by a Hybrid Empirical-Analytical Procedure Based on Peak Ground Acceleration

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Abstract: The seismic risk assessment of existing urban areas provides important information for the process of seismic risk reduction in different phases of planning and emergency management. Between different large-scale assessment approaches, a vulnerability index method is often used for the first screening of the buildings and vulnerability classification. However, this method cannot fully predict the effects of a specific seismic action on buildings. This paper fully extends the scale of the settlement and properly upgrades a methodology previously proposed by authors to predict seismic damage and the risk to a restricted number of masonry buildings in the Croatian settlement Kaštel Kambelovac located along the Adriatic coast. The proposed approach is based on a hybrid empirical-analytical procedure that combines seismic vulnerability indices with critical peak ground accelerations for different limit states computed through a non-linear pushover analysis. The procedure's outcomes are the computation of a relationship linking vulnerability indices to peak ground acceleration for a series of states, corresponding to damage limitation, significant damage, and near collapse. The described methodology is used to estimate seismic risk in terms of damage and the index of seismic risk for selected return periods. The general methodology has allowed a full seismic vulnerability assessment of the whole Croatian settlement of Kaštel Kambelovac.

Keywords: seismic risk assessment; pushover analysis; vulnerability index; damage index; index of seismic risk; masonry buildings

Citation: Nikolić, Ž.; Benvenuti, E.; Runjić, L. Seismic Risk Assessment of Urban Areas by a Hybrid Empirical-Analytical Procedure Based on Peak Ground Acceleration. *Appl. Sci.* **2022**, *12*, 3585. https://doi.org/10.3390/app12073585

Academic Editor: Amadeo Benavent-Climent

Received: 12 March 2022
Accepted: 30 March 2022
Published: 1 April 2022

1. Introduction

The main reason for excessive human losses and material damage during a seismic event is the insufficient seismic resistance of buildings. The assessment of seismic performance of buildings in an existing urban area is a demanding task for civil engineers, especially in old cities that have been gradually growing and expanding over the course of centuries. The heterogeneous distribution of buildings with different architectural, material and structural characteristics, accompanied by different ages of buildings, material degradation over time, various structural and non-structural interventions and, generally, the lack of knowledge about the performance of the structure, lead to numerous uncertainties in the analysis of such structures. Given the complexity of the problem, the assessment of seismic vulnerability and the risk to large areas is usually performed by simplified methods.

The approaches for the evaluation of structural vulnerability can be generally classified as empirical, analytical, or hybrid. Among them, empirical methods are often used for the first screening of buildings and vulnerability classification. The vulnerability index method [1,2] and the damage probability index method [3] are the most common approaches to assess a building's vulnerability at the urban scale. Different versions of the vulnerability index method have been derived from the approach developed by the Italian Defense National Group against Earthquakes (GNDT) for the seismic vulnerability

Fig. 2. The first page of article

2 Scientific reports at the conference

2.1 ECCOMAS-MSF 2021 conference paper "Seismic assessment of historical stone masonry buildings"

UNIST and UNIFE have organized a mini-symposium "Risk assessment and resilience estimation of civil engineering structures and systems", focusing on the PMO-GATE topics in the framework of an international conference ECCOMAS-MSF 2021 held in Split.

UNIST-FGAG staff have presented 2 papers related to PMO-GATE activities. The paper "Seismic assessment of historical stone masonry buildings" [3] has contributed to deliverable 3.3.5. "Scientific reports on open access journals and on the project web site".

The paper has been published in the conference proceedings "5th International Conference on Multi-scale Computational Methods for Solids and Fluids". It is available at the web-site of the project.

The paper is shown in Fig. 3.

ECCOMAS MSF 2021 THEMATIC CONFERENCE
30 June – 2 July 2021, Split, Croatia

SEISMIC ASSESSMENT OF HISTORICAL STONE MASONRY BUILDINGS

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Many countries of moderate to high seismic risk, including Croatia, have old city cores with buildings built of stone or brick long before any regulations on construction in earthquake areas came into force. Some of them are categorized as cultural heritage and should be preserved for future generations. Strong earthquakes cause significant damage and demolition of such buildings and numerous casualties. Rehabilitation requires significant financial resources that cannot be secured at once. Therefore, systematic care and planning is necessary in order to detect the vulnerability of buildings to earthquakes, to determine priorities in rehabilitation and continuously provide funds for the reconstruction of such buildings. Between different approaches for the evaluation of structural vulnerability, static non-linear (pushover) method is recognized as reliable tool for analysis of capacity of structure and failure mechanism.

In this work, seismic vulnerability index method and static non-linear (pushover) analysis are used for seismic vulnerability assessment of stone masonry buildings in the historic city center of Kaštel Kambelovac (Fig.1). The investigation represents one of the activities of the PMO-GATE project, focusing on the preventing, managing and overcoming natural-hazards risks like seismic, floods and extreme sea wave risks.

Fig. 1. Historical center of Kaštel Kambelovac with analysed buildings

The evaluation of the global structural capacity is performed according to Eurocode 8 [1] and corresponding Croatian standard [2, 3]. It is shown for 5 masonry buildings, built between the 15th and 19th centuries. The buildings are made of stone blocks with mortar joints with a thickness of the walls between 45 and 75 cm and flexible wooden floors.

The response of the structure is investigated along the two geometrical orthogonal axes, in both the positive and negative directions. Non-regular distribution of the masses inside the structure is considered by the assumption of an eccentricity of the lateral loads equal to ±5% of the maximum floor dimension at each level. Three lateral load distributions (uniform, linear and modal distribution) with the presence of eccentricity in positive and negative direction give in total 24 analyses.

Each pushover analysis results with the MDOF capacity curve. After the transformation of the MDOF curve in the SDOF one, bilinear curve is obtained. Then, capacity of the structure expressed in peak ground acceleration corresponding to the end of bilinear curve is calculated.

Seismic vulnerability assessment is performed by TREMURI software [4]. Complete 3D models of masonry structures can be obtained assembling 2-nodes macro-elements, representing the non-linear behaviour of masonry panels and piers. The macro-element considers both the shear-sliding damage failure mode and its evolution, controlling the strength deterioration and the stiffness degradation, and rocking mechanisms, with toe crushing effect, modelled by means of phenomenological non-linear constitutive law with stiffness deterioration in compression.

The seismic demand is defined by elastic acceleration response spectrum. Type 1 response spectrum [2] and soil class A [5] are used for HR test site Kastel Kambelovac. The design ground acceleration defined by seismic hazard map for the return period of 475 years is equal to a_g=0.22g. The seismic capacity of the buildings will be defined by checking if the seismic demand represents with 475 years is satisfied.

Numerical predictions of the collapse acceleration by non-linear static analyses show that no building meets the seismic requirement equal to a_g=0.22g in either directions. Namely, the peak ground acceleration corresponding to the collapse of the buildings are in the range of 0.07g and 0.10g. The failure occurs due to different collapse modes such as shear, bending, tension and compression failures. The analyses shows that pushover analysis of stone masonry buildings can provide an insight into both global seismic resistance and the mechanisms that lead to the structural failure. The seismic resistance capacity and obtained vulnerability indexes for chosen buildings are discussed.

Acknowledgements
This work has been supported through the project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact" (PMO-GATE), funded by the European Union through the programme Interreg Italy-Croatia, and the project KK.01.1.1.02.0027, co-financed by the Croatian Government and the European Union through the European Regional Development Fund - the Competitiveness and Cohesion Operational Programme.

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[3] HRN EN 1998-3 Eurocode 8. *Design of structures for earthquake resistance. Part 3: Assessment and retrofitting of buildings*. Croatian Standards Institute, 2011.
[4] TREMURI software. S.T.A.DATA, Professional version, Torino, 2019.
[5] G. Bohm, F. Da Col, F. Accaino, F. Meneghini, A. Schleifer, Ž. Nikolić. *Characterization of shallow sediments in an urban area (Kaštela, Croatia) by analysis of P, SV and Sh seismic velocities using a tomographic approach*, Near Surface Geoscience Conference & Exhibition 2020, 2020, Belgrade, Serbia.

Fig. 3. The paper "Seismic assessment of historical stone masonry buildings"

2.2 Conference paper at the 11th Meeting of the Croatian Society of Mechanics "Methodology for determining of seismic vulnerability curves of stone masonry buildings"

The paper "Metodologija određivanja krivulja potresne ranjivosti kamenih zidanih zgrada" [4] (Eng. Methodology for determining of seismic vulnerability curves of stone masonry buildings) have been presented and published at the Meeting of the Croatian Society of Mechanics. Full paper is given in Proceedings of the 11th meeting of the Croatian Society of Mechanics (Zbornik radova 11. susreta Hrvatskog društva za mehaniku).

The paper is avaliable at the web-site https://www.bib.irb.hr/1145941.

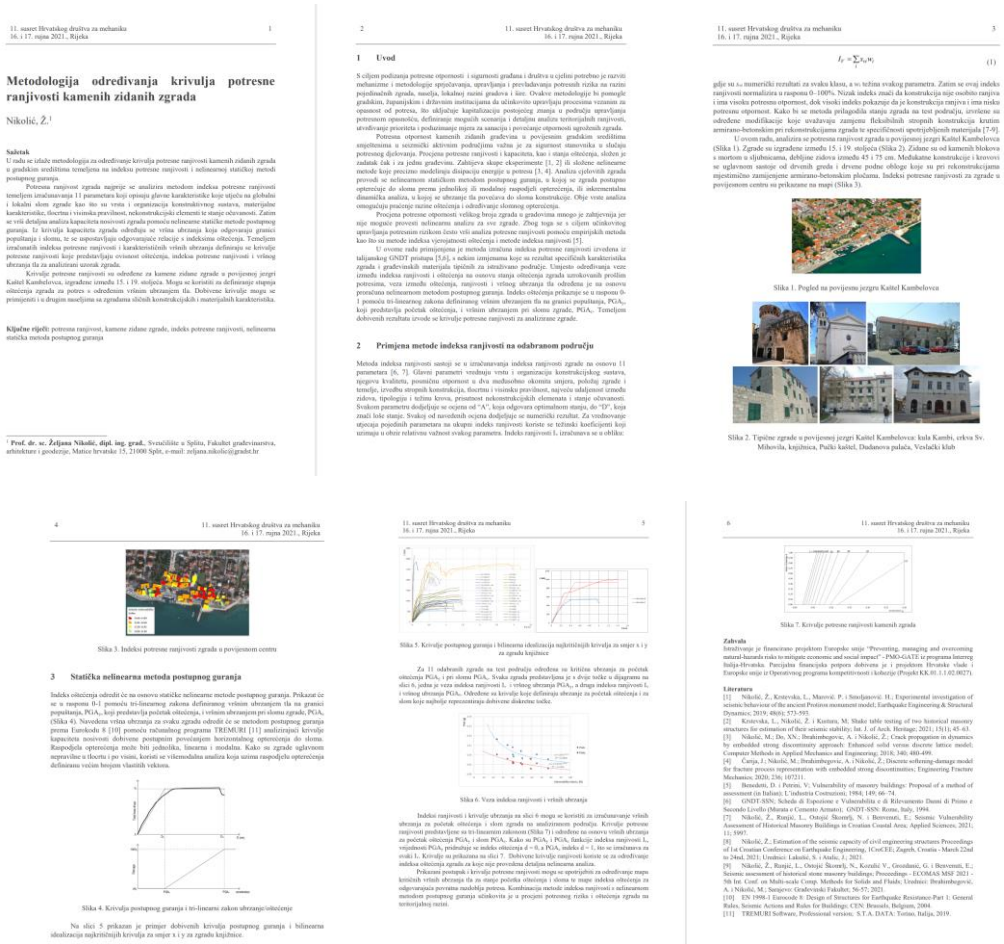

Fig. 4. The paper "Methodology for determining of seismic vulnerability curves of stone masonry buildings"

2.4 Conference paper "Estimation of the seismic capacity of civil engineering structures" at the Proceedings of 1st Croatian conference on earthquake Engineering

The paper "Estimation of the seismic capacity of civil engineering structures" has been presented at the 1st Croatian Conference on Earthquake Engineering (1CroCEE) held in Zagreb. An importance of this presentation is in a fact that, after the high-intensity earthquakes in Croatia with the epicenter in Zagreb and Petrinja in 2020, the research and engineering community are very interested in the methodology for preventing the consequences of such events, developed in the PMO-GATE project. The abstract of the paper is available at the web-site https://crocee.grad.hr/event/1/contributions/108/ . Extended abstract have been published in the Conference Proceedings.

The paper is avaliable at the web-site https://www.bib.irb.hr/1145941.

Proceedings of 1st Croatian Conference on Earthquake Engineering, 1CroCEE
Zagreb, Croatia - March 22nd to 24th, 2021
Edited by Lakusic, S. and Atalic, J.
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ESTIMATION OF THE SEISMIC CAPACITY OF CIVIL ENGINEERING STRUCTURES

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Keywords: Seismic capacity, Collapse mechanism, Historical masonry buildings, Static non-linear analysis.

Estimation of the seismic capacity of existing buildings is of great importance for the safety of inhabitants in the old cities and settlements. This paper presents estimation of the seismic bearing capacity and collapse mechanism of several masonry buildings typical for the historical city centres and surrounding areas along Dalmatian costs (Fig1). The evaluation is performed according to Eurocode 8 [1] and corresponding Croatian standard [2, 3] using static non-linear pushover analysis. Complete 3D models of masonry structures were made by TREMURI software [4] assembling 2-nodes macro-elements, representing the non-linear behaviour of masonry panels and piers. The macro-element considers both the shear-sliding damage failure mode and its evolution, controlling the strength deterioration and the stiffness degradation, and rocking mechanisms, with toe crushing effect, modelled by means of phenomenological non-linear constitutive law with stiffness deterioration in compression.

The response of the structure is investigated along the two orthogonal axes, in both the positive and negative directions. Non-regular distribution of the masses is considered by the assumption of an eccentricity of the lateral loads equal to ±5% of the maximum floor dimension at each level. Three lateral load distributions (uniform, linear and modal) with the presence of eccentricity give in total 24 analyses. Each pushover analysis results with the MDOF capacity curve which transform in bilinear SDOF ones. The capacity of the structure is expressed in peak ground acceleration corresponding to the end of bilinear curve. Type 1 response spectrum [1, 2] and soil class A are used. The design ground acceleration defined by seismic hazard map for the return period of 475 years is equal to a_g=0.22g. The seismic capacity of the buildings is defined by checking if the seismic demand represents with 475 years is satisfied. Local mechanism failure was analysed in order to check local behaviour, such us the lack of connection among perpendicular walls, poor connection among floors/roofs and walls, etc.

Figure 1. (a) Historical centre of Kaštel Kambelovac with stone masonry buildings; (b) Typical family houses outside of historical centre.

Proceedings of 1st Croatian Conference on Earthquake Engineering, 1CroCEE
Zagreb, Croatia - March 22nd to 24th, 2021
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The first group of examples considers stone masonry buildings in the historical city centre of Kaštel Kambelovac (Fig1a) built between the 15th and 19th centuries. They were made of stone blocks with mortar joints with a thickness of the walls between 45 and 75 cm and flexible wooden floors. Numerical predictions of the collapse acceleration by non-linear static analyses show that no building meets the seismic requirement equal to a_g=0.22g in either direction. Namely, the peak ground acceleration corresponding to the collapse of the buildings are in the range of 0.07g and 0.10g. The failure occurs due to different collapse modes such as shear, bending, tension and compression failures. Evaluation of the local mechanism failure shows that critical acceleration yet it arises for the global behaviour. For example, analysis of public library showed that the lowest collapse acceleration is obtained for linear distribution of lateral forces and it is equal to 0.079g, while the lowest value of the failure acceleration in analysis of local mechanism is 0.130g (Fig2).

Figure 2. Results of global and local analysis of Public Library: (a) Critical pushover curve; (b) Critical local mechanism failure.

The second group of buildings are typical family houses (Fig1b) outside of the historical core made as masonry structures consist of concrete or clay blocks without or with concrete boundary elements (beam or/and columns) depending on the construction period. The results for collapse accelerations obtained by pushover analysis are compared for 2-floor and 3-floor buildings made of: (1) unbounded concrete masonry built before the first seismic regulation in 1964; (2) concrete masonry with horizontal RC beams typical for the period between 1964. and 1980.; (3) concrete masonry with horizontal RC beams and RC columns built between 1980. and 2005. and (4) clay masonry with horizontal RC beams and RC columns which are seismically resistant structures due to the applications of modern design standards based on Eurocode 8. Calculated capacity accelerations show that only buildings built according Eurocode 8 meet the seismic requirement.

Acknowledgements

This work has been supported through the project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact" (PMO-GATE), funded by the European Union through the programme Interreg Italy-Croatia, and the project KK.01.1.1.02.0027, co-financed by the Croatian Government and the European Union through the European Regional Development Fund - the Competitiveness and Cohesion Operational Programme.

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[1] EN 1998-1 Eurocode 8 (2004): Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, European Committee for standardization CEN.

[2] HRN EN 1998-1 Eurocode 8 (2011): Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, Croatian Standards Institute.

[3] HRN EN 1998-3 Eurocode 8 (2011): Design of structures for earthquake resistance - Part 3: Assessment and retrofiting of buildings, Croatian Standards Institute.

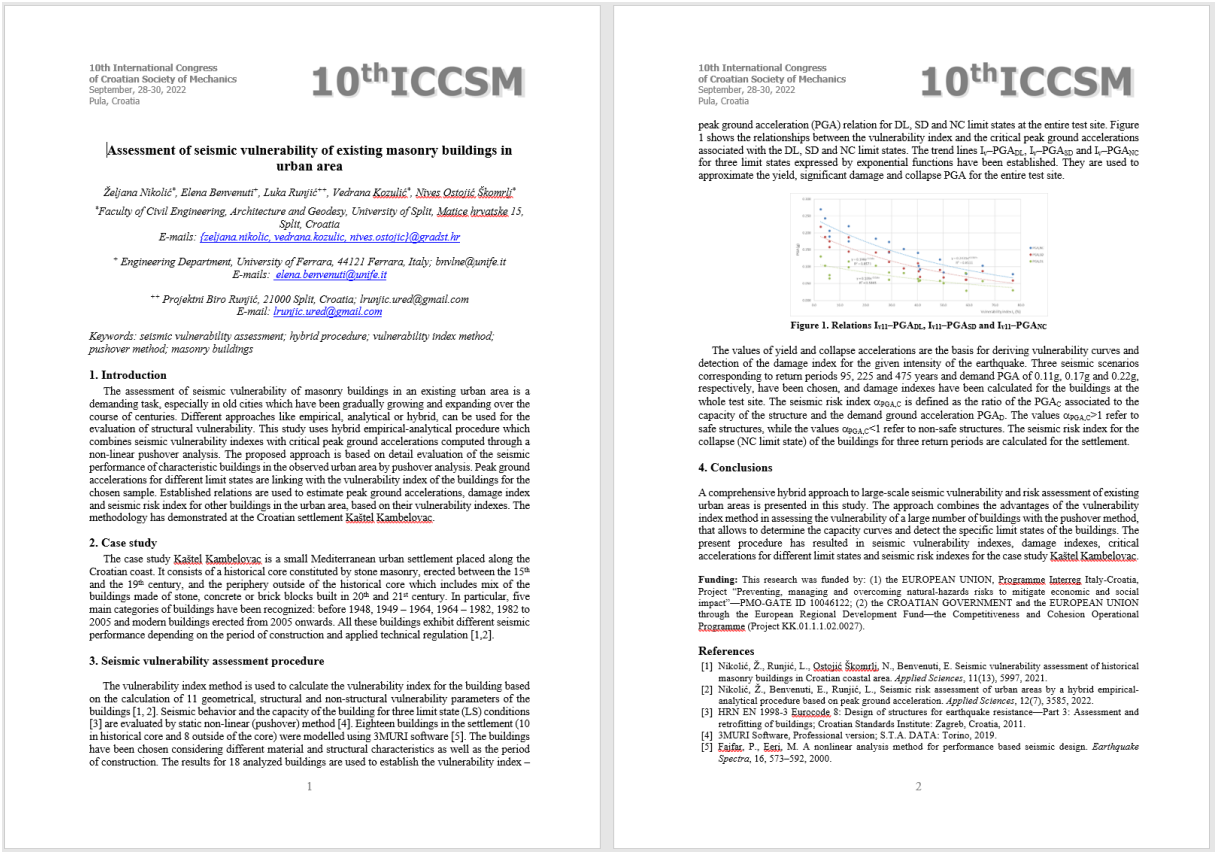
[4] TREMURI software (2019). S.T.A.DATA, Professional version, Torino.

Fig. 5. Two-page abstract of the paper "Estimation of the seismic capacity of civil engineering structures"

2.5 Conference paper "Assessment of seismic vulnerability of existing masonry buildings in urban area" - 10th International Congress of Croatian Society of Mechanics

The paper "Assessment of seismic vulnerability of existing masonry buildings in urban area" will be presented in 10th International Congress of Croatian Society of Mechanics, Pula, Croatia, in September 28-30, 2022. The paper has been submitted to Organized session "Risk assessment and resilience estimation of civil engineering structures and systems" organized by PMO-GATE researchers Željana Nikolić and Elena Benvenuti.

Two-page abstract accepted for presentation is shown in Figure 6.



10th International Congress of Croatian Society of Mechanics
September, 28-30, 2022
Pula, Croatia

10thICCSM

Assessment of seismic vulnerability of existing masonry buildings in urban area

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Keywords: seismic vulnerability assessment; hybrid procedure; vulnerability index method; pushover method; masonry buildings

1. Introduction

The assessment of seismic vulnerability of masonry buildings in an existing urban area is a demanding task, especially in old cities which have been gradually growing and expanding over the course of centuries. Different approaches like empirical, analytical or hybrid, can be used for the evaluation of structural vulnerability. This study uses hybrid empirical-analytical procedure which combines seismic vulnerability indexes with critical peak ground accelerations computed through a non-linear pushover analysis. The proposed approach is based on detail evaluation of the seismic performance of characteristic buildings in the observed urban area by pushover analysis. Peak ground accelerations for different limit states are linking with the vulnerability index of the buildings for the chosen sample. Established relations are used to estimate peak ground accelerations, damage index and seismic risk index for other buildings in the urban area, based on their vulnerability indexes. The methodology has demonstrated at the Croatian settlement Kaštel Kambelovac.

2. Case study

The case study Kaštel Kambelovac is a small Mediterranean urban settlement placed along the Croatian coast. It consists of a historical core constituted by stone masonry, erected between the 15th and the 19th century, and the periphery outside of the historical core which includes mix of the buildings made of stone, concrete or brick blocks built in 20th and 21st century. In particular, five main categories of buildings have been recognized: before 1948, 1949 – 1964, 1964 – 1982, 1982 to 2005 and modern buildings erected from 2005 onwards. All these buildings exhibit different seismic performance depending on the period of construction and applied technical regulation [1,2].

3. Seismic vulnerability assessment procedure

The vulnerability index method is used to calculate the vulnerability index for the building based on the calculation of 11 geometrical, structural and non-structural vulnerability parameters of the buildings [1, 2]. Seismic behavior and the capacity of the building for three limit state (LS) conditions [3] are evaluated by static non-linear (pushover) method [4]. Eighteen buildings in the settlement (10 in historical core and 8 outside of the core) were modelled using 3MURI software [5]. The buildings have been chosen considering different material and structural characteristics as well as the period of construction. The results for 18 analyzed buildings are used to establish the vulnerability index –

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peak ground acceleration (PGA) relation for DL, SD and NC limit states at the entire test site. Figure 1 shows the relationships between the vulnerability index and the critical peak ground accelerations associated with the DL, SD and NC limit states. The trend lines I_V–PGA_{DL}, I_V–PGA_{SD} and I_V–PGA_{NC} for three limit states expressed by exponential functions have been established. They are used to approximate the yield, significant damage and collapse PGA for the entire test site.

Figure 1. Relations I_{V11}–PGA_{DL}, I_{V11}–PGA_{SD} and I_{V11}–PGA_{NC}

The values of yield and collapse accelerations are the basis for deriving vulnerability curves and detection of the damage index for the given intensity of the earthquake. Three seismic scenarios corresponding to return periods 95, 225 and 475 years and demand PGA of 0.11g, 0.17g and 0.22g, respectively, have been chosen, and damage indexes have been calculated for the buildings at the whole test site. The seismic risk index $\alpha_{PGA,C}$ is defined as the ratio of the PGA_C associated to the capacity of the structure and the demand ground acceleration PGA_D. The values $\alpha_{PGA,C}>1$ refer to safe structures, while the values $\alpha_{PGA,C}<1$ refer to non-safe structures. The seismic risk index for the collapse (NC limit state) of the buildings for three return periods are calculated for the settlement.

4. Conclusions

A comprehensive hybrid approach to large-scale seismic vulnerability and risk assessment of existing urban areas is presented in this study. The approach combines the advantages of the vulnerability index method in assessing the vulnerability of a large number of buildings with the pushover method, that allows to determine the capacity curves and detect the specific limit states of the buildings. The present procedure has resulted in seismic vulnerability indexes, damage indexes, critical accelerations for different limit states and seismic risk indexes for the case study Kaštel Kambelovac.

Funding: This research was funded by: (1) the EUROPEAN UNION, Programme Interreg Italy-Croatia, Project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact"—PMO-GATE ID 10046122; (2) the CROATIAN GOVERNMENT and the EUROPEAN UNION through the European Regional Development Fund—the Competitiveness and Cohesion Operational Programme (Project KK.01.1.1.02.0027).

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Fig. 6. Two-page abstract "Assessment of seismic vulnerability of existing masonry buildings in urban area"

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