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Definition of seismic vulnerability of existing residential buildings and buildings for family housing in Polog Valley

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Abstract— Methodologies for evaluation of seismic vulnerability of existing residential buildings and structures for family housing have been investigated. A procedure for evaluation of seismic vulnerability of RC buildings has been proposed. Applying the nonlinear static "pushover" analysis, the parameters of nonlinear behavior of the selected set of reinforced concrete buildings have been defined. There have also been defined the vulnerability indices as a measure of damage to each building, as a scaled linear combination of the state of nonlinear behavior of the components at the point of termination of the "pushover" analysis. The computed values of vulnerability indices obtained by "pushover" analysis to the range of 0.2 – 0.3 point to satisfactory behavior of the analyzed buildings.

Index Terms—Seismic vulnerability, RC buildings, pushover, vulnerability index

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1 Introduction

THE latest earthquakes that happened all over the world have raised the awareness of the need for realistic assessment of possible consequences of future earthquakes, particularly in seismically active areas. Many countries have already realized such projects of possible scenarios including different databases that are the basis of each research. The usual procedure of creation of a database on the construction fund in a region by use of typified forms is presented. Finally, a form that could be implemented on our cities is proposed.

This paper deals with a topical problem in the field of vulnerability of existing structures to seismic effects. The present regulations in the domain of seismic design in our country have neither been updated since 1981, when the last regulations for seismic design were passed, northey treat the reliability of the constructed structures from any aspect. Presently, this is a very important field of research in the world wherefore it is very important to initiate collection of data and creation of a database necessary for getting an insight into the existing conditions. This paper represents an attempt to assess the seismic risk in the territory of a selected region in RM, i.e., the Polog valley.

Recent procedures for evaluation of vulnerability of buildings have primarily been focused on the structural system, capacity, project and response parameters. These parameters enable a more realistic evaluation of the expected behavior when a built structure reflects the prescribed structural and architectonic characteristics and conditions.

Reinforced concrete structures are the most frequently used types of structural systems of reinforced concrete buildings in this region. Although the present seismic regulations enable satisfying behavior of reinforced concrete buildings, there is still a big number of seismically weak-inadequate structures that have not been proved to comply with these regulations. The identification of weak structures is of a great importance for the assessment of losses in case of possible strong future earthquakes and establishment of priority criteria for the strengthening of these structures.

A brief review is given regarding the existing concepts of exploration of vulnerability of buildings as well as methodologies for analysis of seismic vulnerability. A general review of the geographic position, relief, cities and municipalities that exist in the region, the seismicity of the region, the seismic risk and maps from the physical plan, the seismic hazard potential, the seismological and epicentral map of the Polog valley as a seismically active area, is also given. The percentage of built-up area, the presence of individual types of buildings are described and selected buildings for analysis are indicated.

Recommendations for displacement based design are given and the steps and methods used in the analysis are described. The nonlinear static pushover analysis as a procedure for evaluation of the seismic response of reinforced concrete buildings is described and an illustrative example elaborated by application of the SAP2000 software is given.

A review of investigations of the vulnerability of reinforced concrete frame structures in seismic regions as well as modeling and analysis necessary for assessment of damage is also given. The current conditions prevailing in the considered region are discussed and an approach to definition of damage is described along with an example taken from literature. The uncertainties, the mode and the documents used in modeling of the buildings, the characteristics of the materials, the calibration of the stiffness parameters and the procedure for vulnerability assessment by pushover analysis are presented, as well. Description of the analyzed structures and categorization of the selected structures in the Polog valley are given, along with identification of the key elements that affect the behavior of structures in seismic conditions. The realized

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analysis and the mode of computation of the vulnerability index of the structures are described.

The paper also shows the results from the performed investigation of the vulnerability of the existing reinforced concrete residential structures and structures for family housing in the populated rural and urban places in the Polog valley. A simplified methodology for definition of the seismic resistance of these structures is proposed.

The proposed methodology represents a combination of a micro- and macro approach to analysis of the seismic vulnerability of existing structures. Namely, a nonlinear static analysis of the beaviour of the selected set of 20 characteristic structures is carried out at the level of an integral structure. Such an approach belongs to the group of methods that involve micro-modeling.

After obtaining the response of the selected representative structures, the results from the nonlinear static analysis of the structures have been used to derive general conclusions on the level of seismic vulnerability of an entire class of buildings enabled by their design according to the current regulations. Such an approach represents a typical example of a macro-approach to seismic vulnerability analysis.

The proposed methodology that represents a combination of micro- and macro-modeling represents an innovative approach to providing relevant data on a whole class of structures in a smaller region, treating also the specific characteristics of the structures from the considered class of buildings, represented, in this case, by the reinforced concrete residential structures and structures for family housing in inhabited rural and urban places in the Polog valley.

The research has been carried out within the frames of a doctoral thesis [1] and should be seen in the light of the conditions prevailing in the construction and design practice in the last two decades of independence of the Republic of Macedonia. Namely, due to institutional changes and the long delay in passing of the Law on Construction, the wider public is seriously worried about the level of seismic resistance possessed by the structures built in that period. The selection of the subject of research, namely residential structures in the Polog valley arose, first of all, due to the expansive growth of these inhabited places in the considered period.

During the research, much attention was paid to the exploration of the existing construction fund in the selected region whereat typization of characteristic structural solutions was made. For the selected structures, detailed information on the structural and nonstructural elements was gathered, providing authenticity, originality and, first of all, reliability of the derived conclusions.

2 ANALYZED STRUCTURES

Individual residential structures for family housing and collective residential buildings were considered in the investigations presented in this paper. A total of 50 structures were analyzed. A detailed description is given for 20 structures located in different municipalities of the Polog region [1]. Some of the structures have business premises – premises for different purposes at their ground floors. Most of the analyzed structures are located in Gostivar and Tetovo, while some of them are situated in the rural municipalities. The analyzed structures are with different number of storeys and are located on different locations. According to the number of storeys, the structures were classified into three categories as follows: up to GF+3, up to GF+5 and from GF+5 to GF+10 storeys.

TABLE 1.
CONSIDERED STRUCTURES PER MUNICIPALITIES

Number of storeys	Gostivar municipality, number of investigated structures	Tetovo municipality, number of investigated structures	Rural municipalities, number of investigated structures
Up to GF+3 storeys	12	6	10
Up to GF+5 storeys	8	6	
Up to GF+10 storeys	2	6	

Each structure was identified by ordinal number, address/location, investor, date of construction, description of type of structure, number of storeys and structural system.

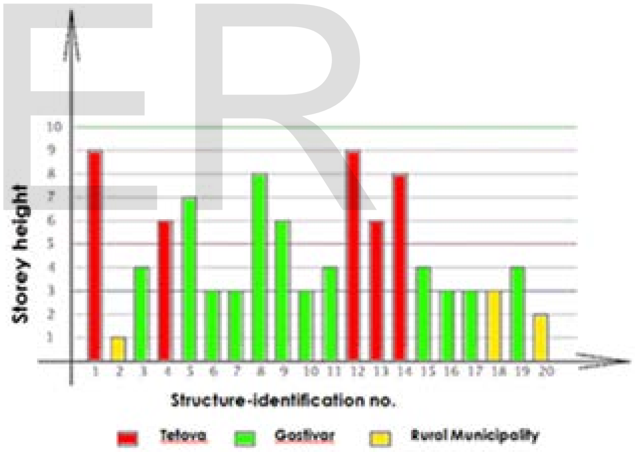

Figure 1 Marked structures per municipalities

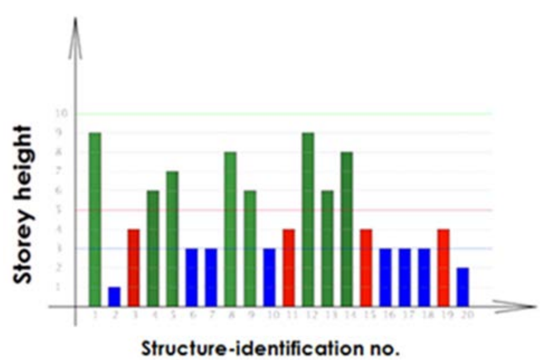

Figure 2. Marked structures per number of storeys

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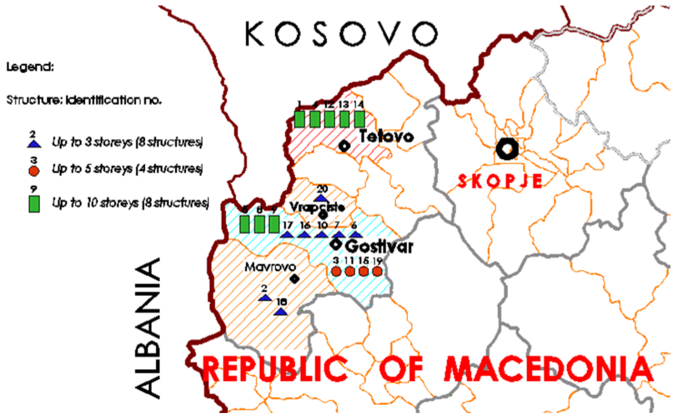

Figure 3. Analyzed structures

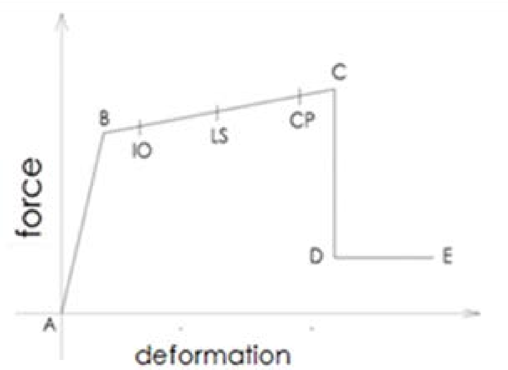

Figure 4. Force-displacement curve for the plastic hinges

3 PERFORMED ANALYSIS AND RESULTS

SAP2000 computer programme was used to carry out non-linear static pushover analysis of reinforced concrete buildings. The location of the plastic hinges was selected at the cross-sections of the structural elements where the first achievement of static quantities causing yielding was expected. Under the effect of horizontal loads, such cross-sections are most frequently located at the ends of the structural elements. Hence, the plastic hinges were located at the ends of all beams and all columns of a structure, as places of the first occurrence of ultimate moments [2].

The vulnerability index defined with the pushover analysis is a measure of damage to a building. It is defined as a scaled linear combination (weighted mean) from the measures of behavior of plastic hinges formed in elements and is computed from the levels of behavior of elements at the performance point or at the moment of termination of the pushover analysis. The vulnerability index of a building is computed by use of the following expression:

$$V_I build. = \frac{1.5\sum N_i^c x_i + \sum N_i^h x_i}{\sum N_i^c + \sum N_i^h} \qquad (1)$$

where, N_i^c and N_i^h represent number of formed plastic hinges in the columns and the beams, respectively, for the i-th level of behaviour (i=1,2,…..,6) , [2].

The force-deformation curve for the plastic hinges was divided into 6 levels of behavior as follows: *B-IO*, *IO-LS*, *LS-CP*, *CP-C*, *D-E*, and > *E*. Upon accomplishment of the analysis, the level of deformed state of each hinge can be seen from the out-output results on the deformed state. A weighted factor x_i is assigned to each level of behavior, as given in Table 3. The results also show the number of formed hinges in the beams and the columns of a structure. The columns are treated as elements of a greater importance for the global safety of a building wherefore they are assigned a weighted factor of 1,5 unlike 1,0 assigned for the beams [2].

TABLE 2.

Range	Factor x_i
<B	0
B to IO	0.125
IO to LS	0.375
LS to CP	0.625
CP to C	0.875
C-D, D-E, >E	1

From the analysis, the capacity curves (relationship between total seismic force at the base and the maximum horizontal displacement at the top) of the buildings were obtained. These curves provide an insight into the behavior of the structures, their evaluated minimal seismic bearing capacity, their stiffness and maximum displacement.

The obtained pushover curves also show the values of seismic forces for the structures designed according to the current regulations for seismicity of VII, VIII and IX degrees that are relevant for the considered region of the Polog valley [1].

In all structures, a considerable reserve of bearing capacity can be observed. This points out the conservativeness of the current regulations.

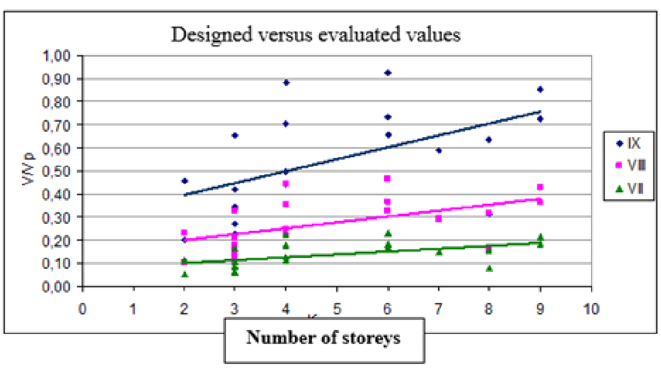

Figure 5. Relationship between the seismic bearing capacity and the bearing capacity evaluated by pushover analysis for seismicity of VII, VIII and IX degrees

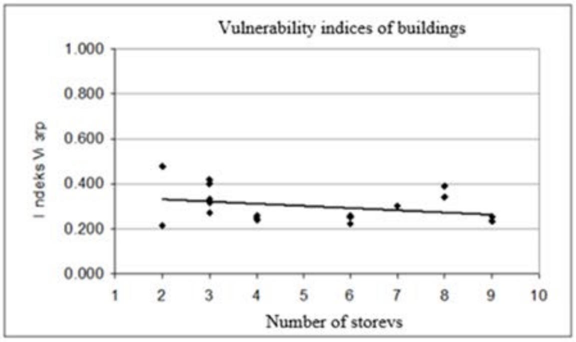

Figure 6. Vulnerability indices of buildings

TABLE 3.
RELATIONSHIPS OF DESIGNED SEISMIC BEARING CAPACITY OF BUILDINGS

Structure	Number of storeys	V_{IX}/V_p	V_{VIII}/V_p	V_{VII}/V_p
1	9	0,46	0,23	0,11
2	1	0,20	0,10	0,05
3	4	0,65	0,33	0,16
4	6	0,35	0,17	0,09
5	7	0,33	0,17	0,08
6	3	0,27	0,13	0,07
7	3	0,42	0,21	0,10
8	8	0,22	0,11	0,06
9	6	0,70	0,35	0,18
10	3	0,50	0,25	0,12
11	4	0,88	0,44	0,22
12	9	0,45	0,22	0,11
13	6	0,73	0,37	0,18
14	8	0,66	0,33	0,16
15	4	0,93	0,46	0,23
16	3	0,58	0,29	0,15
17	3	0,31	0,16	0,08
18	3	0,63	0,32	0,16
19	4	0,73	0,36	0,18
20	2	0,85	0,43	0,21

It can be observed that the computed values of the vulnerability index are considerably uniform and that there are no significant deviations [1].

4 CONCLUSION

With the application of the proposed methodology and analysis of the behavior of 20 selected representative structures with number of storeys ranging from two to nine, the following conclusions from the investigations can be drawn:

- Most of the reinforced concrete buildings with 2 to 9 storeys exhibit a satisfactory behavior. The bearing capacity of the buildings was estimated by means of a pushover analysis pointing to existence of considerable reserves in respect to the forces computed according to the current regulations.
- The obtained values of the vulnerability indices of the buildings range from 0,2 to 0,4, with the exception of buildings with irregularities at plan and along height for which values of indices higher than 0,45 were obtained.
- Nonlinear behavior of the structures is exerted mainly through formation of plastic hinges in the beam elements.
- From the analysis of the deformed state of hinges formed in the beams, it can be concluded that the conditions of these hinges are in the range between B and IO. Until the occurrence of the first plastic hinges in the columns, the conditions regarding the hinges in the beams are in the range of IO-LS. The analysis ends when the conditions of hinges formed in the columns are in the range between LS-CP, which corresponds to effective displacement of about 2-3% of the height of the buildings.
- A simple method that enables evaluation of the seismic vulnerability of existing RC buildings has been developed. The method is based on consideration of the capacity of the buildings for nonlinear deformation in conditions of seismic effects.
- The proposed method is a useful tool for the achievement of this goal since it allows analysis of vulnerability of buildings that are commonly found in a certain territory, including data from different sources and of different preciseness.

It remains to be pointed out that all the above presented conclusions should be considered with a certain reservation arising from the fact that all the performed analyses were mainly based on data obtained from design documentation, while possible deviations in the process of construction is a situation that cannot be excluded. Hence, in applying the considered methodology on individual structures, it is necessary to pay particular attention to the agreement between the design documentation and the as-built state of the structure.

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