SEISMIC VULNERABILITY OF RC BUILDINGS IN POLOG VALLEY

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SUMMARY

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. The vulnerability indices as a measure of damages to each building have been defined and computed in the form of 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 the vulnerability factors obtained by "pushover" analysis are in the range of 0.2-0.3 and point to satisfactory behavior of the analyzed buildings.

Key words: *vulnerability, RC buildings, "pushover" analysis, vulnerability index*

INTRODUCTION

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 R. Macedonia have not only been not upgraded since 1981 when the last regulations on seismic design were passed, but they do not at all treat the reliability of constructed structures. Presently, this is a very important field of research in the world. Hence, it is of a big importance to launch an initiative for acquisition of data and creation of a data base necessary for getting an insight into the existing conditions.

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The research presented in this paper was carried out by a simple procedure of seismic risk assessment on the territory of the selected region in RM, or more precisely, the Polog valley. The selection of the subject of research was motivated, first of all, by the extensive growth of these populated places in the indicated period. The selected structures were categorized and the key elements affecting the behavior of the structures in seismic conditions were identified.

Reinforced concrete frame structures are the most frequently present type of a structural system that is used for buildings in this region. Although current seismic regulations enable satisfying behavior of reinforced concrete buildings, there is still a big number of seismically weak-inadequate structures whose compliance with these regulations has still not been proved. Identification of seismically weak structures is therefore of a great importance in assessing the losses in the case of a possible future strong earthquake and establishing priority criteria for strengthening of these structures.

Modern procedures for assessment of vulnerability of buildings are primarily focused on the structural system, the capacity, the project and the response parameters. These parameters will enable a more realistic assessment of the expected behavior if the constructed structure reflects the prescribed structural and architectonic characteristics and conditions.

The proposed methodology represents a combination of micro and macro approach to analysis of the seismic vulnerability of existing structures. Namely, at the level of the integral structure, a nonlinear static analysis of the behavior of the selected set of 20 characteristic structures was carried out. Such an approach belongs to the group of methods that involve micro-modeling. After obtaining the response of the selected representative structures, the results of the nonlinear static analysis were used in drawing general conclusions on the level of seismic vulnerability of a whole class of structures designed in accordance with the valid regulations. Such an approach represents a typical example of a macro-approach to analysis of the seismic vulnerability.

Nonlinear static "pushover" analysis as a procedure for assessment of the seismic response of reinforced concrete buildings was carried out by use of the SAP2000 computer programme [8]. Using the parameters of nonlinear behavior of the structural elements obtained by nonlinear analysis, a simplified methodology for definition of the seismic resistance of these structures through computation of the vulnerability indices of the buildings is proposed.

ANALYZED STRUCTURES

In the research presented in this paper, individual residential structures for family housing and collective residential buildings were considered. Twenty structures in different municipalities of the Polog region were analyzed [1].
Some of the structures contain business premises at the ground floor for different purposes. Most of the analyzed structures are in Gostivar and Tetovo, while some are located in the rural municipalities. The analyzed structures are with a different number of storeys and are situated on different locations.
According to the number of storeys, the structures are divided into 3 categories as follows**: up to GF+3, up to GF+5 and from GF+5 to GF+10 storeys,** as shown in Table 1. Table 2 displays the analyzed structures according to type, structural system, year of construction and number of storeys.

Table 1. Considered structures per municipalitie

Number of storeys	Number of structures in Gostivar included in the research	Number of structures in Tetovo included in the research	Number of structures in rural municipalities included in the research
Up to GF+3 storeys	12	6	10
Up to GF+5 storeys	8	6	
Up to GF+10 storeys	2	6	

The data in Table 2 show that the structures were constructed in the period 1997 to 2011. Most of them represent individual and collective residential buildings with a height of up to 6 storeys. It can also be observed that all the selected structures have a reinforced concrete structural system consisting of RC frames and RC slabs as floor structures.

Table 2. Analyzed structures according to type of structural system, year of construction and number of storeys

Identificat. no.of the structure	**Type of structure**	**Structural elements**	**Dat**	**Number of storeys**
No.1	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2002	**9**
				B+GF+M+5+A
	Weekend house-	Reinforced		**1**

No.2	individual residential building	Concrete frames and RC slab	2002	**B+GF**
No.3	Individual residential building with business premises	Reinforced Concrete frames and RC slab	2002	**4** **B+GF+2**
No.4	Collective residential building with business premises	Reinforced Concrete frames and RC slab	1999	**6** **B+GF+4**
No.5	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2006	**7** **B+GF+4+A**
No.6	Individual residential building	Reinforced Concrete frames and RC slab	Пред 1997	**3** **GF+2(1+A)**
No.7	Individual residential building	Reinforced Concrete frames and RC slab	2008	**3** **B+GF+1**
No.8	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2011	**8** **B+GF+5+A**
No.9	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2006	**6** **B+GF+3+A**
No.10	Individual residential building - duplex	Reinforced Concrete frames and RC slab	2009	**3** **S+GF+1**
No.11	Individual residential building with business premises	Reinforced Concrete frames and RC slab	2009	**4** **B+GF+2**
No.12	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2008	**9** **B+GF+7**
No.13	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2004	**6** **B+GF+4+A**
No.14	Collective residential building with business premises	Reinforced Concrete frames and RC slab	2008	**8** **B+GF+6**
No.15	Individual residential building with business premises	Reinforced Concrete frames and RC slab	2009	**4** **B+GF+2**
No.16	Individual residential building	Reinforced Concrete frames and RC slab	2005	**3** **B+GF+1**
No.17	Individual residential building	Reinforced Concrete frames and RC slab	1997	**3** **GF+2**
No.18	Weekend house-individual residential	Reinforced Concrete frames and	2009	**3** **B+GF+A**

	building	RC slab		
No.19	Individual residential building with business premises	Reinforced Concrete frames and RC slab	2006	**4** **B+GF+2**
No.20	Individual residential building – duplex	Reinforced Concrete frames and RC slab	2009	**2** **GF+1**

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

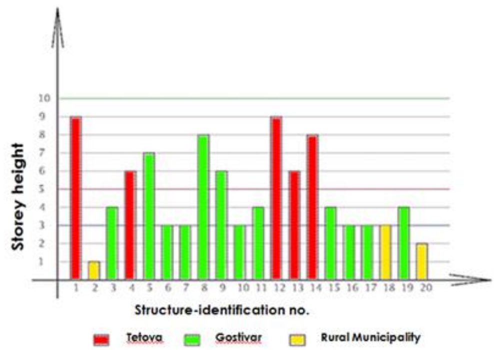

Figure 1. Structures marked per municipalities

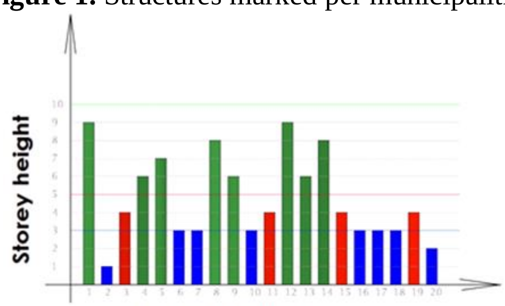

Figure 2. Structures marked per number of storeys

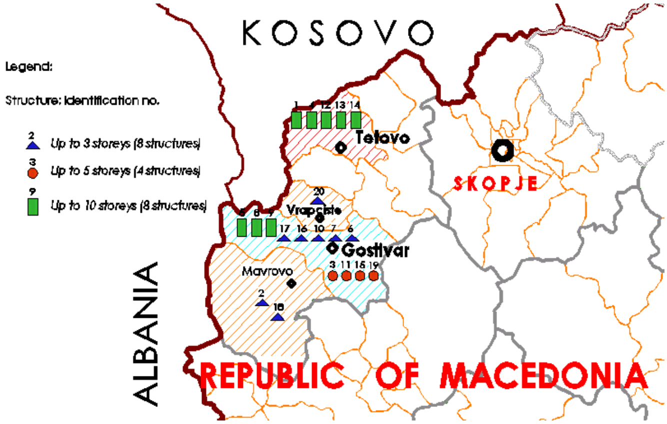

Figure 3. Location of the analyzed structures

ANALYSIS AND RESULTS OBTAINED

To evaluate the bearing capacity of the selected reinforced concrete buildings, a nonlinear static "pushover" analysis was carried out by use of the SAP2000 computer programme. Plastic hinges were selected to take place in the cross-sections of the structural elements where initial reaching of the 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, plastic hinges were located at the ends of all the beams and at the ends of all the columns of the structure as places to be the first to reach the ultimate moments [2].

With the performed nonlinear static "pushover" analysis, the capacity curves for all the selected buildings were obtained as relationships between the total seismic force at the base and the maximum horizontal displacement at the top. These curves could provide an insight into the behavior of the structures, their minimal evaluated seismic bearing capacity, structural stiffness and maximum displacement.

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

$$F_{I_{3rp}} = \frac{1.5\sum N_i^c x_i + \sum N_i^h x_i}{\sum N_i^c + \sum N_i^h} \qquad (1)$$

where, N_i^c and N_i^h represent the 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*, Figure 4. Upon completion of the analysis, the level of deformation could be seen from the output results on each hinge. Each level of behavior was assigned a corresponding weighted factor, x_i as shown in Table 3.

The analysis also enabled the obtaining of the number of formed plastic hinges in the beams and the columns of the structure. The columns were treated as elements of a greater importance for the global safety of the building wherefore they were assigned a weighted factor of 1,5 unlike the weighted factor of 1,0 for the beams, [2].

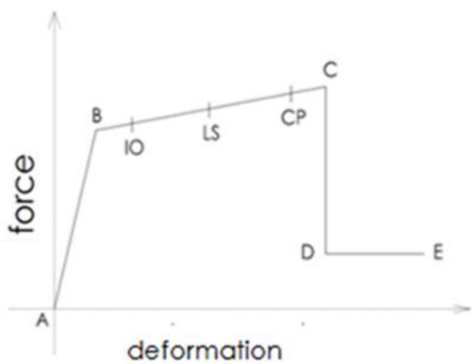

Table 3

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

Figure 4. Force-displacement curve for the plastic hinges

The evaluated transverse bearing capacity of the structures was compared with the designed bearing capacity, i.e., the values of the seismic forces for the structures designed according to the currently valid regulations with seismicity coefficients of VII, VIII and IX degrees that are relevant for the considered region of the Polog valley [1].

What can be observed in all structures is that there are considerable reserves of bearing capacity evaluated by nonlinear analysis, indicating conservatism of the currently valid regulations.

Table 4 shows the relationships between the designed values of seismic forces and the evaluated transverse bearing capacities of the buildings for different seismicity coefficients. A considerable reserve of bearing capacity of the structures is evident.

Table 4. Relationship between the designed and evaluated bearing capacity of the buildings

Structure	**Number of storeys**	**V_{IX} /Vp**	**V_{VIII} /Vp**	**V_{VII}/Vp**
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

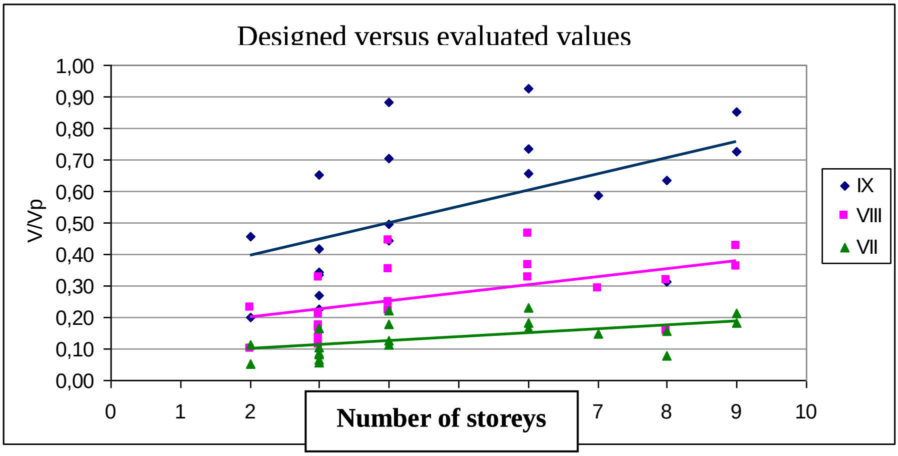

Figure 5. Relationship between the designed seismic bearing capacity and the bearing capacity evaluated by the "pushover" analysis for seismicity of VII, VIII and IX degrees.

A graphic presentation of the relationships between the designed bearing capacity and the capacity of the structures evaluated by nonlinear analysis is given in Figure 5.
Figure 6 shows the computed vulnerability indices for the buildings obtained by use of expression (1). It can be observed that the computed values of the vulnerability indices are considerably uniform and range within the limits of 0,2-0,45, [1].

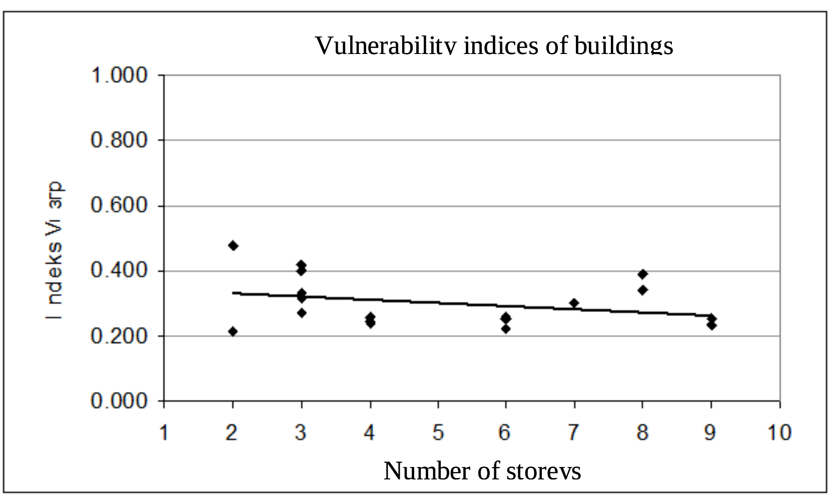

Figure 6. Vulnerability indices for the analyzed structures

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The results from the nonlinear analysis and the data used for the computation of the vulnerability index refer to the analyzed building no. 3, representing an individual residential building with business premises, with 4 storeys (B + GF + 2). The building is structurally solved by reinforced concrete columns and beams. The floor structure of the building represents a reinforced concrete slab.
Figure 8 shows view of the structure and its vertical cross-section, while the plan of the characteristic storey of the building is shown in Figure 7.

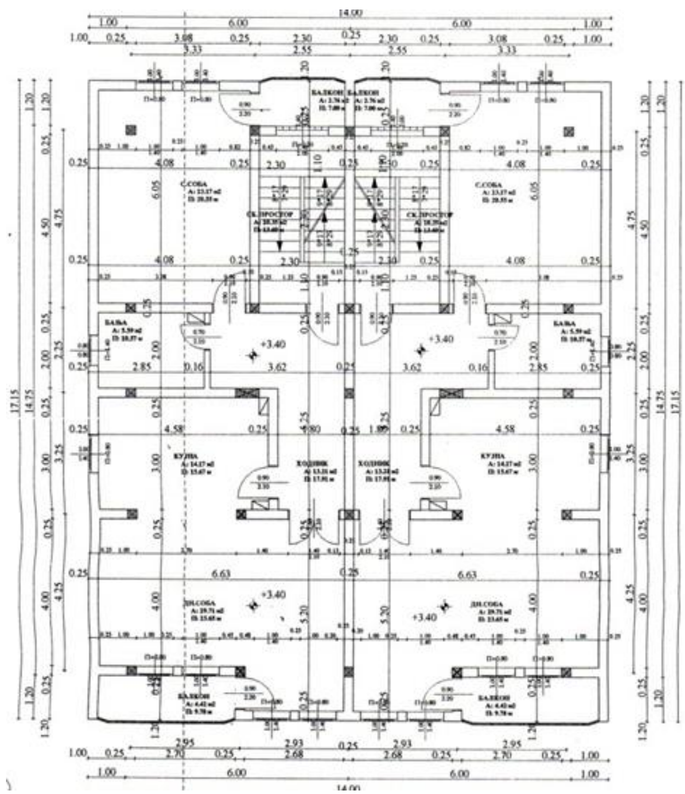

Figure 7 Plan of characteristic storey of the building

Figure 8. View and cross-section of the building

The obtained curve of transverse bearing capacity is shown in Figure 9. Presented further are the values for the computation of the vulnerability index of the same structure.

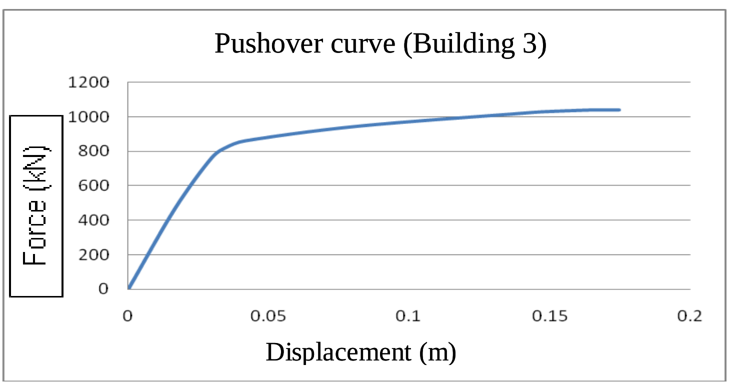

Figure 9: Pushover-curve for structure no. 3

Tables 5 and 6 display the values necessary for the computation of the vulnerability index of the structure (number of formed plastic hinges in the structural elements, columns and beams and the corresponding factors of nonlinear behavior).

Table 5: Number of plastic hinges formed in the beam elements of structure no. 3

Structure 3 – beams			
Plastic hinge range	Number of plastic hinges (N_i^h)	Factor(xi)	Ni*Xi
<B	515	0	0
B to IO	45	0.125	5.625
IO to LS	15	0.375	5.625
LS to CP	25	0.625	15.625
C-D, D-E, >E	40	1	40
Σ	640		66.875

Table 6: Number of plastic hinges formed in the elements – the columns of structure no. 3

Structure 3 - columns			
Plastic hinge range	Number of plastic hinges (N_i^h)	Factor(xi)	Ni*Xi
<B	325	0	0
B to IO	31	0.125	3.875
CP to C	17	0.875	14.875
C-D, D-E, >E	25	1	25
Σ	398		43.75

$$VI = \frac{1.5 \cdot 43.75 + 66{,}875}{398 + 640} = 0.128$$

The computed value of the vulnerability index of structure no. 3 amounts to 0.128.

CONCLUSIONS

From the performed analysis and the obtained parameters of behavior of the selected structures, the following conclusions are drawn:

- Most of the reinforced concrete buildings with 2 to 9 storeys behave satisfactorily. The bearing capacity of the buildings evaluated by means of "pushover" analysis points to the existence of considerable reserves in respect to the forces computed according to the currently valid regulations.
- The obtained values of the vulnerability indices of the buildings are within the limits of 0,2 to 0,4 with the exception of the buildings with irregularities at plan and along height for which values of indices higher than 0,45 were obtained.
- The nonlinear behavior of the structures is mainly through formation of plastic hinges in the beam elements.
- From the analysis of the deformed state of the hinges formed in the beams, it can be concluded that the conditions of these hinges range between B and IO. Until the occurrence of the first plastic hinges in the columns, the conditions of the hinges in the beams range between IO-LS. The analysis ends when the conditions of the hinges formed in the columns are in the range between LS-CP, corresponding 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 is applied. In this method, the capacity for nonlinear deformation of the structural elements of the buildings under seismic effects is taken into account.
- The proposed method is a useful tool for achieving this goal since it enables analysis of the vulnerability of ordinary buildings in a certain territory including data from different sources and of different preciseness. It should be pointed out that all the performed analyses were mainly based on data obtained from design documentation whereat possible deviations from these data in the process of construction is a situation that cannot be excluded. Hence, when applying the indicated methodology on individual structures, it is necessary to pay particular attention to the correspondence between the design documentation and the "as built" state of the structure.

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