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Research paper

SEISMIC PERFORMANCE ASSESSMENT OF AN EXISTING RC BUILDING IN ROZAJE ACCORDING TO EN 1998-3

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Abstract

Given that Montenegro is located in a region with a high seismic hazard, assessing the seismic performance and retrofitting of existing buildings is crucial for reducing seismic risk. This presents a significant challenge in modern construction, as most existing buildings were designed according to outdated regulations, making them non-compliant with contemporary seismic standards and necessitating structural retrofitting. This research focuses on the seismic assessment of an existing reinforced concrete (RC) frame building in Rožaje, with the aim of verifying the compliance with the significant damage limit state as defined by the European standard EN 1998-3. The analysis of the existing building, modeled in the ETABS software package, was carried out using non-linear static Pushover analysis. Material and structural nonlinearity characteristics were defined, along with the plastic mechanism and nonlinear loading, all in accordance with EN 1998-3. The Pushover analysis was conducted in 50 steps, during which the predefined plastic mechanism demonstrated the formation of plastic hinges within the structure. The results indicated that while the building does not meet the significant damage limit state, its deformation capacities remain within acceptable limits, whereas shear capacity is exceeded. Consequently, it was concluded that shear retrofitting of specific structural elements (beams and columns) is necessary to meet the EN 1998-3 requirements. FRP (Fiber Reinforced Polymer) materials were identified as the optimal solution for retrofitting. This study provides valuable insights into the seismic performance of similar structures in Rožaje and other Montenegrin cities, offering a basis for improving seismic resilience in line with modern regulations.

Key words: *Seismic assessment, RC building, EN 1998-3, retrofitting, Non-linear static Pushover analysis*

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1. INTRODUCTION

Given that Montenegro is located in a region of high seismic hazard, the assessment of seismic performance and the seismic strengthening of existing structures are of critical importance for reducing seismic risk. Evaluating the behavior of buildings under earthquake loading and ensuring adequate seismic safety prior to the occurrence of a seismic event remains a significant challenge in structural engineering today. Most existing buildings were designed according to outdated codes, such as PIOVS 1981 [1] and Temporary Code 1964 [2], and therefore do not possess adequate seismic resistance. Moreover, they fail to meet the seismic design requirements specified in modern European standards, particularly EN 1992-1-1 [3], EN 1998-1 [4] and EN 1998-3 [5]. Consequently, these buildings require structural strengthening. Assessing the seismic performance for buildings designed according to old codes and designing appropriate retrofit measures to achieve acceptable seismic behavior has become a highly relevant and pressing issue in the field of structural engineering in Montenegro.

As no comprehensive vulnerability assessment of the built environment has yet been conducted in Montenegro, this study aims to contribute to the evaluation of existing reinforced concrete (RC) residential buildings in the municipality of Rožaje. The objective is to assess the seismic performance of a selected representative RC building type, with a focus on verifying the limit state of significant damage in accordance with the EN 1998-3 [5]. The analysis will evaluate both the bending and shear resistance and deformation capacities of structural elements (beams and columns), and propose optimal seismic strengthening solutions for selected components. The proposed retrofitting strategies will emphasize both economic efficiency and ease of technical implementation. By achieving these objectives, the study will provide valuable insights into the seismic safety of existing buildings exposed to earthquakes in the Rožaje area and contribute to a broader understanding of the seismic vulnerability of RC buildings. The seismic performance assessment, particularly the verification of the significant damage limit state as defined by EN 1998-3 [5], will be conducted using a nonlinear static pushover analysis. For the purpose of this study, data on multi-family residential buildings will be sourced from the Municipal Earthquake Protection and Rescue Plan for Rožaje (OPZiS, 2017) [6], as well as available design and planning documentation obtained from the municipal archive of Rožaje.

2. SELECTION OF A REFERENCE RC BUILDING IN ROŽAJE

Based on the analysis of the available planning and design documentation, the building shown in Figures 1, 2, and 3 was selected as a representative example of typical buildings in the municipality of Rožaje. The selected building is a RC frame structure, has base dimensions of 40.75m by 14.0m. It consists of a basement with a height of 2.77m, a ground floor with a height of 3.57m and five floors, each with a height of 2.79m [7]. One of the key factors influencing its selection as the reference building is the well-documented construction history, which provides a solid foundation for a comprehensive seismic assessment. The availability of complete data from the original design documentation allows for a detailed and accurate seismic analysis. In addition to representing a typical frame-structure building found in Rožaje, the selected building is also among the larger structures constructed in recent years, giving it urban significance and making its seismic safety particularly important to the local community, further justifying its selection for this research. RC frame systems have distinctive characteristics with respect to seismic performance and are among the most commonly used structural systems in seismically active regions. These structures are defined by a skeletal arrangement of beams and columns, offering high flexibility and effective dissipation of seismic energy during earthquake events.

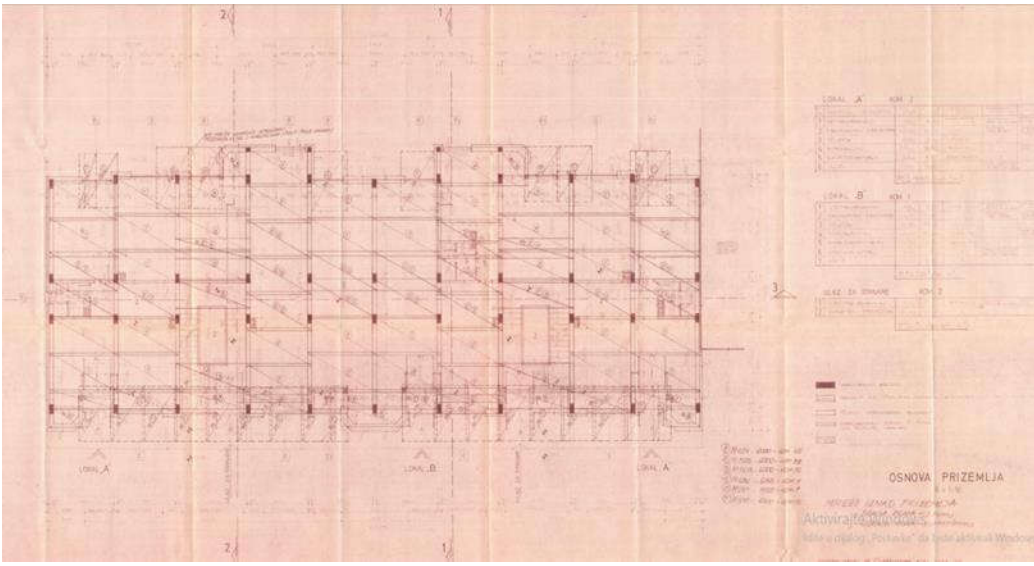


Figure 1. Ground floor plan extracted from the available design documentation

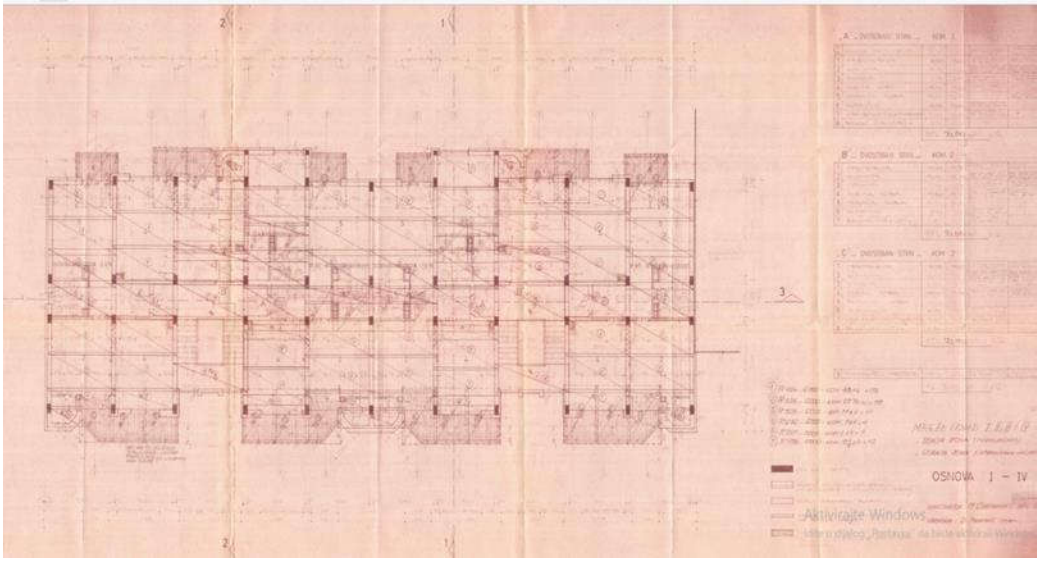


Figure 2. Typical floor plan (Levels I–IV) extracted from the available design documentation

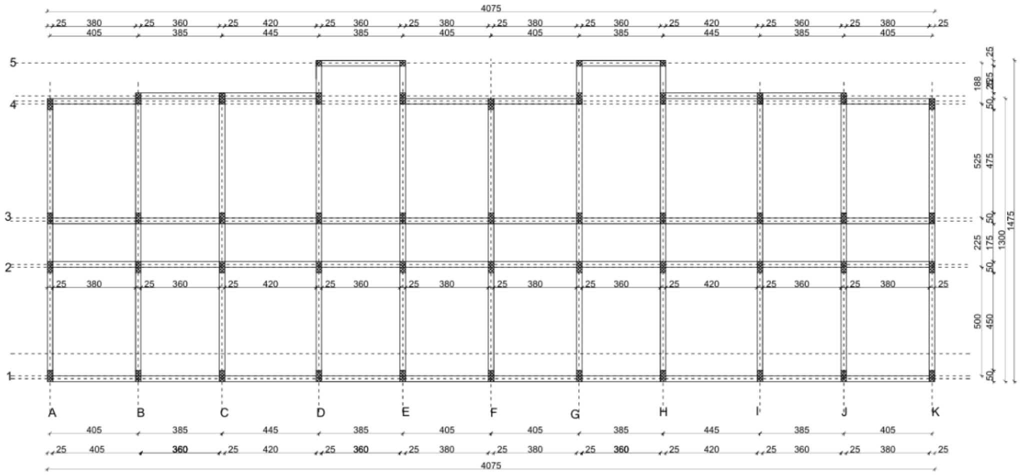


Figure 3. Typical floor plan (Levels I-IV) extracted from the autoCad

Given that the building has been in use for an extended period, serving both residential and commercial purposes, the analysis of its characteristics, seismic resistance, and potential retrofitting methods provides valuable insight into the real challenges and opportunities for enhancing the seismic performance of such structures.

While RC frame structures have advantages in terms of seismic performance, due to their inherent flexibility and ductility, they nonetheless require detailed analysis, particularly when design standards have evolved since the time of construction (in this case, 1985). The analysis of the selected building's frame system will provide valuable insights into the seismic behavior of such structures in Rožaje. Consequently, this research may serve as a reference for similar buildings, not only in Rožaje but also in other municipalities across Montenegro, offering practical recommendations for improving and modernizing seismic resistance in accordance with current standards and techniques. In doing so, the study contributes to the long-term safety of communities and the protection of the urban built environment.

3. SEISMIC ASSESSMENT OF A SELECTED RC BUILDING ACCORDING TO EN 1998-3

Prior to conducting nonlinear static analysis, it is essential to perform a structural condition assessment of the building under investigation. This process involves determining whether the existing structure satisfies the required performance at a defined limit state under the considered seismic action. In this study, the assessment focuses on verifying the Significant Damage (SD) limit state in accordance with EN 1998-3 [5]. Seismic performance evaluation of existing structures requires input data gathered from various sources, including available documentation, field surveys, in-situ or laboratory testing, and measurements. According to EN 1998-3 [5], the data required for structural evaluation should include: (1) identification of the structural system and its compliance with regularity criteria defined in EN 1998-1 [4]; (2) determination of the building's foundation type; (3) classification of soil conditions based on EN 1998-1 [4]; (4) data on global dimensions, cross-sectional properties of structural elements, and mechanical properties of materials used; (5) identification of material deficiencies and detailing inadequacies; (6) information on the seismic design criteria applied in the original design, including the behavior factor (q-factor), where applicable; (7) description of the current or intended use of the building; (8) updated load assessments reflecting the building's functional use; and (9) data on the type and extent of past and existing structural damage, if any, including records of previous retrofitting measures.

An essential subsequent step in the assessment of an existing structure is the determination of the knowledge level, as defined in EN 1998-3 [5]. Knowledge levels represent varying degrees of reliability in the information collected about a building and are particularly important in the evaluation of existing structures.

Before performing any structural analysis or implementing retrofitting measures, it is essential to determine the achievable level of knowledge. A higher knowledge level corresponds to greater reliability of the analysis results. The selection of an appropriate type of analysis and the corresponding confidence factor, reflecting the accuracy and reliability of the available data, should be based on the established knowledge level. As the knowledge level increases, the confidence factor decreases, leading to a more realistic and accurate assessment of the structural condition.

Three levels of knowledge are defined:

1. Knowledge Level 1 (KL1): Corresponds to a limited amount of information available about the structure.
2. Knowledge Level 2 (KL2): Represents a standard level of knowledge, based on more detailed investigation of the structure, including material sampling and testing to obtain more accurate data on material properties.
3. Knowledge Level 3 (KL3): Corresponds to complete knowledge, based on the most comprehensive investigation and documentation of the structure.

The factors that determine the appropriate knowledge level include: the geometric properties of the structural system and non-structural elements that may influence the structural response; detailing, including the quantity and layout of reinforcement in RC elements; and the mechanical properties of the materials used in the structure.

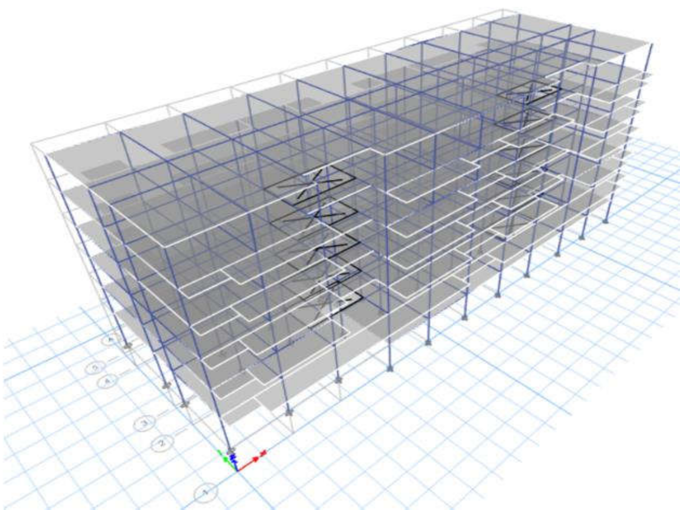
Based on the available design documentation and the analysis of the factors defining the knowledge level, it was concluded that the selected reference building corresponds to Knowledge Level 2 (KL2), i.e., a normal level of knowledge.

The condition assessment procedure can be carried out using general analysis methods specified in EN 1998-1 [4], with modifications outlined in EN 1998-3 [5]. The following types of analyses may be employed: a) Linear analyses: Lateral Force Method and Modal Response Spectrum Analysis; b) Nonlinear analyses: Static (Pushover) Analysis and Dynamic (Time History) Analysis and c) Approach based on the application of the behavior factor (q-factor).

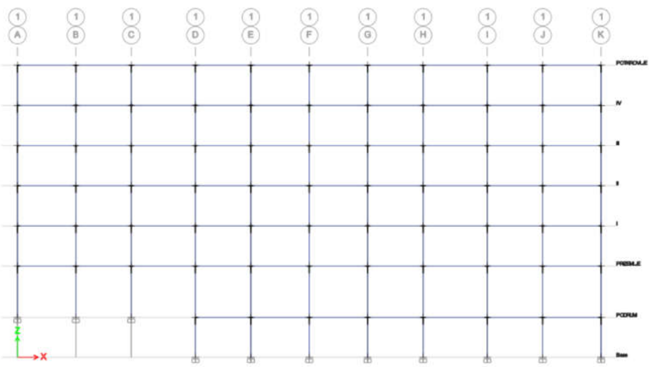
For the selected building, the most appropriate method for obtaining a comprehensive understanding of its seismic behavior is the nonlinear static pushover analysis. This choice is based on the fact that the criteria for applying linear methods, as defined in EN 1998-3, were not fully met. Specifically, the lateral force method did not satisfy the requirements related to the fundamental period of vibration. As a result, modal response spectrum analysis was initially applied, with floor forces calculated according to EN 1998-1 [4]; however, the conditions required by EN 1998-3 [5], which is the focus of this assessment, were still not satisfied. Consequently, nonlinear Push-over analysis was adopted.

3.1. Non-linear modelling

The analyzed RC building was modeled using the ETABS software package [8] (Figure 4). For the purposes of the nonlinear pushover analysis, moment–curvature diagrams were generated within the same software environment. The development of these diagrams required the adoption of nonlinear material properties for both concrete and reinforcing steel. The moment–curvature diagram was used to define the yield moment M_y and the corresponding yield curvature θ_y as well as the ultimate moment M_u and the corresponding ultimate curvature θ_u. To define the properties of confined concrete, it was first necessary to determine the properties of unconfined concrete for the corresponding concrete grade, as presented in Table 1. For the selected building, concrete of class C25/30 was assumed, in accordance with EN 1992-1-1 [3]. Both confined concrete and reinforcing steel were modeled in accordance with the provisions of EN 1992-1-1 [3] and EN 1998-3 [5]. After defining the nonlinear material properties, plastic hinges were assigned to the cross-sections of columns and beams.



(a)



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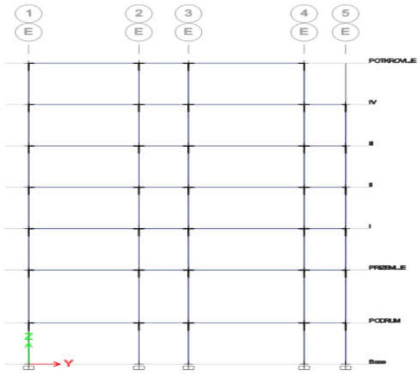


(c)

Figure 4. a) 3D view of the modeled RC building in the ETABS software package [8], b) Elevation of the X-direction typical frame and c) Elevation of the Y-direction typical frame

Table 1. Properties of unconfined concrete

Concrete class C25/30	
Characteristic compressive strength f_{ck} $[MP_a]$	25
Mean compressive strength f_{cm} $[MP_a]$	3,3
Mean value of the modulus of elasticity E_{cm} $[GP_a]$	31
ε_{c2} [‰]	2,0
ε_{cu2} [‰]	3,5

Figure 5 illustrates the definition of plastic hinge properties for nonlinear analysis in ETABS [8], applied to one of the representative beams. Given that the beam is subjected to a negligibly small axial force and primarily loaded in bending about a single axis, the definition of the plastic hinge requires only a moment–curvature diagram, without the need for interaction diagrams, thus, an M3 plastic hinge is appropriate.

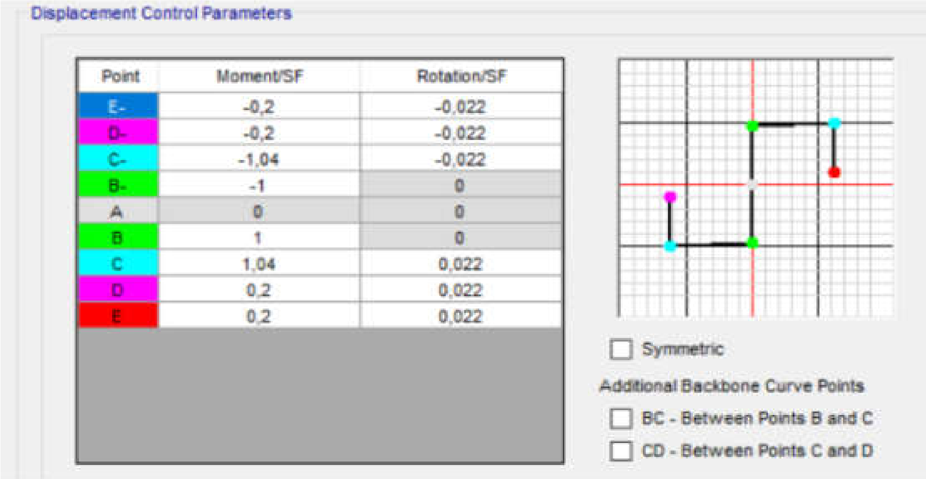


Figure 5. Definition of a beam plastic hinge in the ETABS software package [8]

Figure 6 shows the definition of a column plastic hinge for nonlinear analysis. Since axial compressive force significantly influences column behavior, it is necessary to consider biaxial bending and axial loading. Therefore, a P–M2–M3 plastic hinge is defined for the column, incorporating an interaction diagram that accounts for biaxial bending combined with axial force.

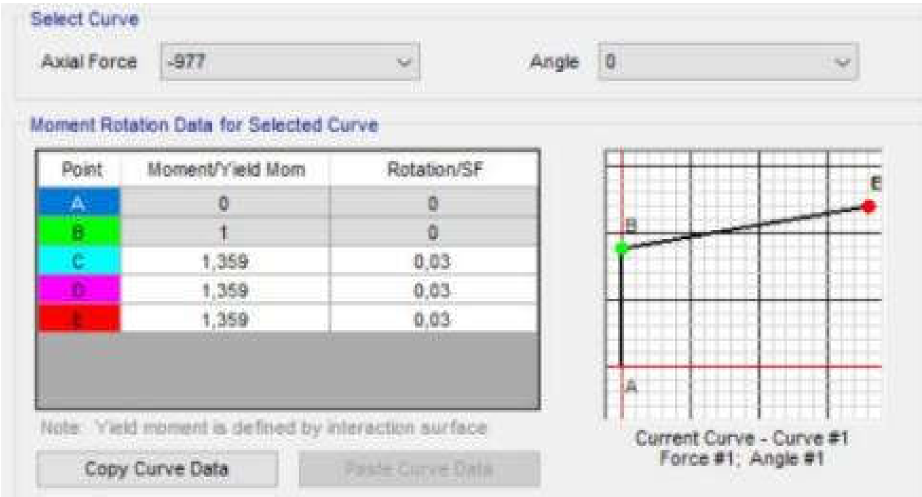


Figure 6. Definition of a column plastic hinge in the ETABS software package [8]

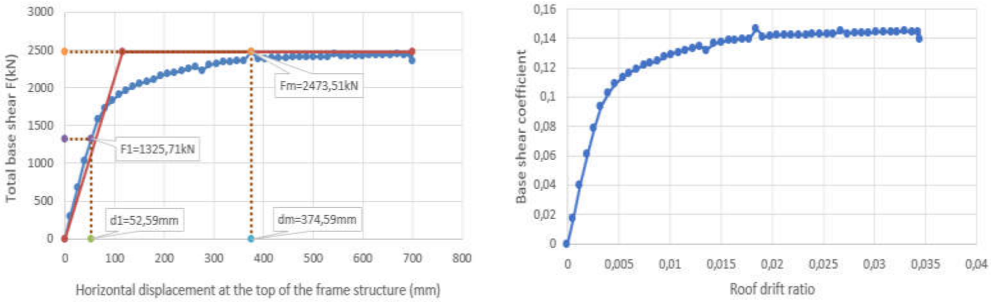
Subsequently, the nonlinear loading was defined. The first step involved the definition of nonlinear gravitational loading. In accordance with EN 1998-3 [5], two load distributions, modal and uniform, were specified for both the X(+/-) and Y(+/-) directions.

3.2. Non-linear static Pushover analysis

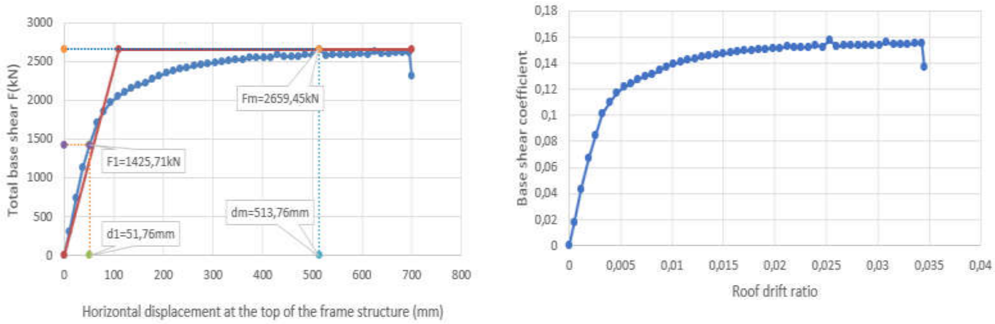
The pushover analysis was conducted in ETABS software package [8]. The outcome of the analysis is the pushover curve, which describes the relationship between the base shear and the displacement at the top of the structure [9]. This curve was used to determine the target displacement, which in turn provided the control displacements required for further structural analysis. The target displacement was calculated in accordance with EN 1998-1

(Annex B) [10], by transforming the multi-degree-of-freedom (MDOF) system into an equivalent single-degree-of-freedom (SDOF) system using the elastic response spectrum.

Figures 7 and 8 present the pushover curves obtained using the ETABS software [8] for both the X and Y directions, considering both lateral load distributions (modal and uniform). These curves were used to determine the control displacements, which served as the basis for the final results.

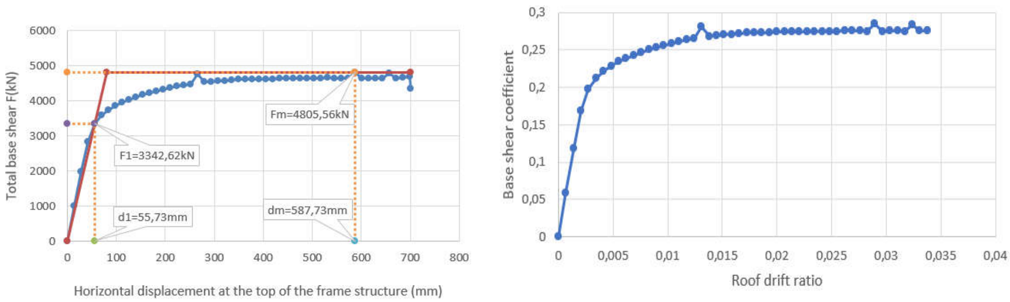


(a)

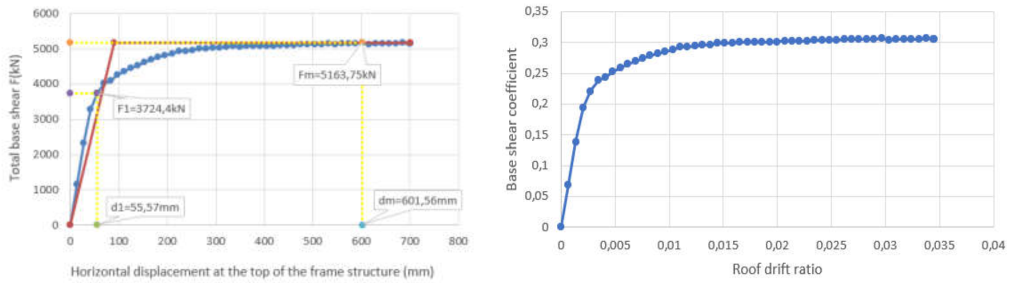


(b)

Figure 7. Pushover curves in the X+ direction: a) modal load distribution and b) uniform load distribution



(a)

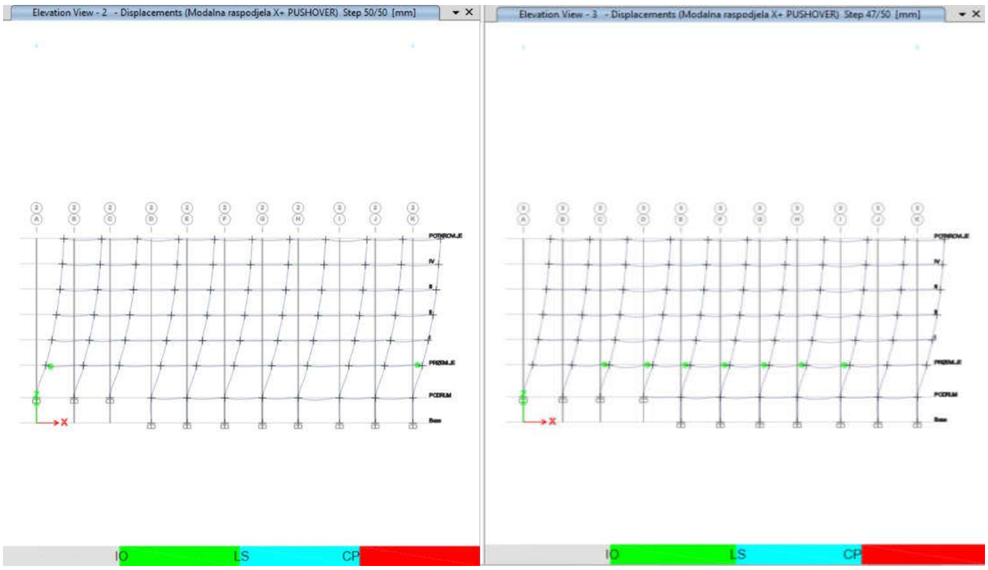


(b)

Figure 8. Pushover curves in the Y+ direction: a) modal load distribution and b) uniform load distribution

Figure 9. illustrates the formation of plastic hinges for modal distribution in X+ direction, shown for the frame along axis 2 at step 50/50 and the frame along axis 3 at step 47/50, respectively. Figure 10 presents the behavior of one of the plastic hinges observed in the aforementioned frames.

Specifically, while the deformation capacities were not exceeded, the shear capacity was surpassed, leading to the conclusion that the Significant Damage (SD) limit state was not satisfied. Consequently, seismic strengthening of certain structural elements (beams and columns) is required, with a focus on enhancing their shear resistance. Since the shear capacity was exceeded, it was necessary to consider structural strengthening in accordance with EN1998-3.



(a) *(b)*

Figure 9. Loading case with "modal distribution X+": a) frame along axis 2 – plastic hinge formation at step 50/50, and b) frame along axis 3 – plastic hinge formation at step 47/50

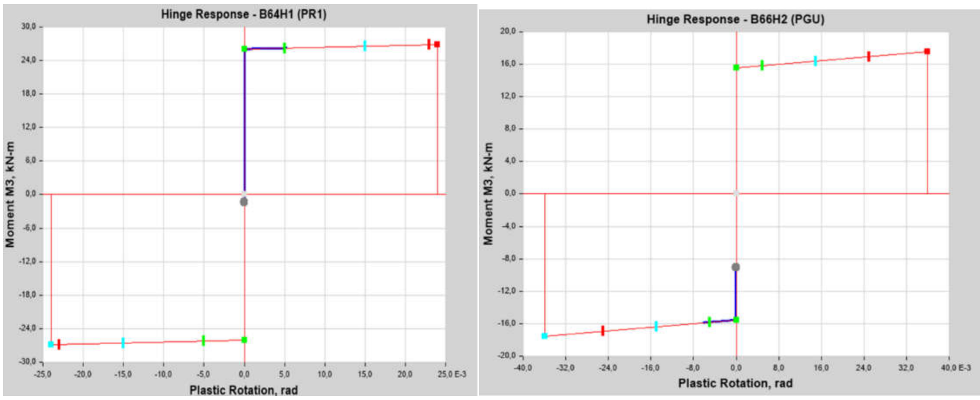
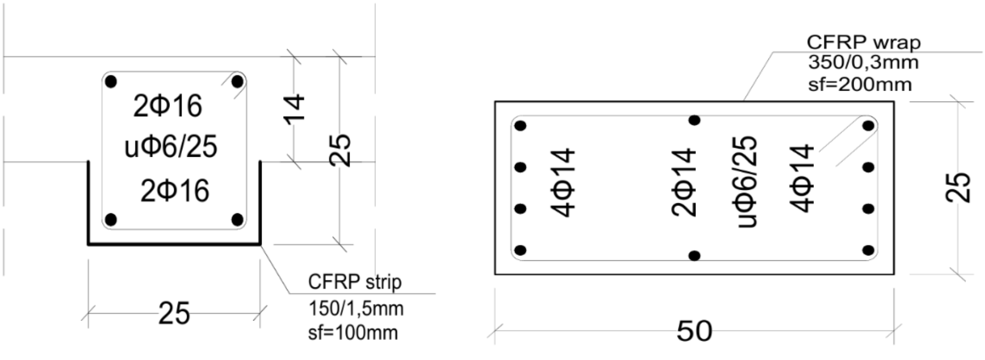


Figure 10. Behavior of one of the plastic hinges – deformation capacities not exceeded

4. SEISMIC RETROFITTING OF RC BUILDING USING FRP MATERIALS

Various strengthening techniques are available for structural elements, including concrete or steel jacketing, confinement with additional reinforcement, and the use of Fiber Reinforced Polymer (FRP) systems such as FRP laminates and wrapping. These methods aim to enhance load-bearing capacity, increase bending and shear strength, and improve deformation capacity. In this study, FRP materials, specifically carbon FRP (CFRP) strips and wraps, were selected as the strengthening solution. A key advantage of FRP-based retrofitting, compared to conventional methods, is the ability to carry out the intervention within a short time frame, even while the building remains in use. Figure 11 illustrates beam strengthening using CFRP strips and column strengthening using CFRP wraps.



(a) *(b)*

Figure 11. Example of strengthening: a) beam retrofitted with CFRP strips, and b) column retrofitted with CFRP wraps

5. CONCLUSIONS

The analysis of the selected building provides important insights into the seismic behavior of such structures in Rožaje. Accordingly, this study may serve as a reference for similar buildings throughout Montenegro, offering recommendations for improving and modernizing seismic resistance in line with current design practices and technologies, thereby contributing to long-term community safety and the protection of the urban built environment.

The assessment was carried out using nonlinear static pushover analysis, which demonstrated that the deformation capacities were not exceeded. However, subsequent evaluation of shear capacity revealed that, for certain structural elements, shear demands exceeded capacity, indicating that the Significant Damage (SD) limit state was not satisfied. As a result, seismic strengthening of structural elements with respect to shear is necessary to ensure that the structure can adequately dissipate seismic energy in a controlled manner without experiencing brittle failure, given that deformation capacity remains within acceptable limits.

To enhance shear resistance and overall seismic performance, strengthening using CFRP strips was adopted as the optimal solution due to its economic viability and ease of implementation. The use of CFRP materials contributes to increased load-bearing capacity of structural elements without a significant increase in the structure's self-weight.

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