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# Capacity Evaluation and Spectral Analysis of Damaged Low-Rise Reinforced Concrete Building

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**Abstract**

Numerous buildings sustained damage during the November 26, 2019, earthquake in Durres, particularly in the cities of Durres, Kruja, and Tirana. The majority of existing older buildings in these regions lack adequate seismic safety measures due to deficiencies in their original designs. Furthermore, these structures were often constructed with substandard workmanship and, in many cases, without the involvement of professional engineers. This paper focuses on the in-situ investigation of one such building to assess the extent of damage. A comprehensive analysis is performed, encompassing material tests, geological assessments, and seismic hazard evaluations conducted on both the building and its construction site. The building is then modeled using existing material properties through specialized software, and various analyses, including modal analysis, capacity evaluation, and spectrum analysis, are carried out. The empirical results derived from these analyses are subsequently compared with the observed damage to the building. In light of the findings, the paper explores potential retrofitting techniques aimed at repairing the current structural deficiencies. The proposed strategies are discussed with the goal of aligning the structure with the requirements outlined in Eurocode 8.

**Keywords***:* reinforced concrete building, seismic damage evaluation, pushover capacity analysis, spectrum seismic assessment

## INTRODUCTION

On November 26, 2019, an earthquake struck the central-western part of Albania. This earthquake was assessed with a magnitude of Mw = 6.4 [1]. The main tremor and subsequent aftershocks caused damage to buildings in Durrës, Tirana, and several settlements in the wider area. The predominant types of buildings in the building stock of Albania are structures with massive load-bearing walls, buildings with reinforced concrete skeleton systems, and non-load-bearing walls made of bricks or concrete blocks. In some cases, mixed systems are also observed. The majority of current buildings have been constructed based on the technical design codes of KTP, which were first implemented as legal provisions in 1963 and were improved and updated in 1978 and 1989 [2].

Most existing buildings with load-bearing walls as well as reinforced concrete skeleton structures, as in many European countries, were designed taking into account previous seismic codes (KTP-63, KTP-78, KTP-89), where seismic loads were either not considered or were considered very low during the design phase. This leads to a deficiency in seismic safety measures in the design of these buildings [3]. The analyzed structure is a residential building with a living area of 750 m², located in Fushë-Krujë, Krujë. The building was constructed around the first years of the 1990s and has a regular geometric structure in both plan and dimensions, with some additions in various parts. The existing conditions of the building were assessed based on a thorough inspection on-site, taking into account modern construction codes related to seismicity, such as EC-6 and EC-8.

When the parameters of this earthquake are compared with the probabilistic seismic hazard map (NATO SfP Project No. 983054), it is observed that this earthquake, in terms of the maximum induced horizontal acceleration, closely aligns with and easily surpasses values associated with a seismic event with a return period of 95 years [4], [5]. According to EC-8, for this level of seismicity, the structure should perform at the DL (damage limitation) performance level, characterized by minor damage, primarily in non-structural elements, for the building. For this earthquake, the structure should be undamaged and operate in the elastic phase.

## LITERATURE REVIEW

The Eurocodes that will serve as a basis for drafting this paper are:
EN1990 Eurocode: Basics of structural design [6]
EN1991 Eurocode 1: Action of structures [7]
EN1992 Eurocode 2: Design of concrete structures [8]
EN1993 Eurocode 3: Design of steel structures [9]
EN1996 Eurocode 6: Design of masonry structures [10]
EN1990 Eurocode 7: Geotechnical design [11]
EN1990 Eurocode 8: Design of structures for earthquake resistance [12]

Eurocode 8 provides the fundamentals of seismic design and calculation of structures. According to this code, seismic force depends on the maximum ground acceleration and the type of soil. From this factors is derived the elastic spectrum.

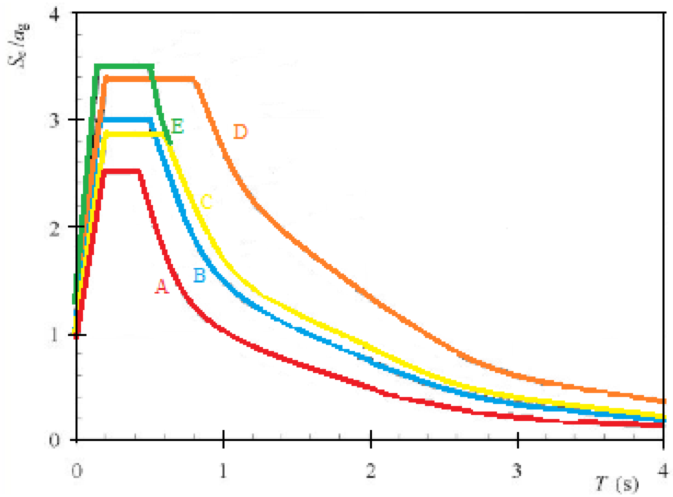


**Figure 1.** Elastic spectrum according to EC-8 [12]

The above spectrum (elastic) is converted into an inelastic spectrum following the procedure outlined in Eurocode 8 (EC-8), and ultimately, it is presented as a function of spectral acceleration and spectral displacement. This approach is employed to compare the capacity of the structure with the spectrum. In the end, conclusions are drawn regarding the performance and condition of the structure in the event of a specific earthquake. By definition, the capacity of the structure is the maximum level of horizontal force it can withstand without collapsing (this is when the building is loaded, including with vertical gravity loads, etc.). According to Eurocode 8 [12], the structural capacity of the building is assessed through non-linear pushover analysis. It is presented in terms of the force-displacement graph, indicating the force at the base and the maximum displacement of the idealized model box with a degree of freedom of the structure. For ease of calculation, the capacity curve is often taken as bilinear, clearly distinguishing the initial elastic phase from the subsequent plastic phase.

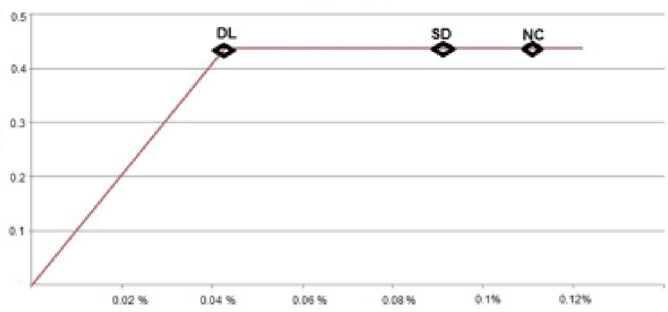


**Figure 2.** Capacity curve of the object [12]

The performance level of a structure refers to the expected degree of damage the structure sustains after a specific earthquake. Eurocode 8 [12] classifies three performance levels as follows:

**DL - Damage Limitation** In this phase, there is no structural damage to the building, but there may be damage to non-structural elements. Most elements operate in the elastic phase, and the structure is ready to continue its functionality.

**SD -** Significant **Damage** In this phase, there is structural damage to the building, but it is reparable and does not pose a threat to the lives of occupants. Most elements have surpassed the elastic phase, and some may reach their plastic capacity, resulting in various deformations. The structure requires reconstruction before resuming functionality.

**NC - Near Collapse** In this phase, there is severe structural damage to the building, and the lives of occupants may be at risk. Most elements operate in the plastic phase, and there may be local collapses. At this stage, the building is likely economically impractical to repair, as the cost of repair approaches or exceeds the cost of reconstruction.

## FIELD INVESTIGATION AND THE CONDITION OF THE SITE AFTER THE EARTHQUAKE OF NOVEMBER 26, 2019

### *The geometric characteristics of the structure*

"The examined structure, a residential building covering an area of 750 m², is situated in Fushë-Krujë near Krujë. Constructed around the 90s, the building exhibits a regular geometric structure in both plan and dimensions, with additional elements incorporated in various sections. The basement boasts a height of 5.45m and an area of 230 m². The first floor features a height of 3.30 m and an area of 270 m², while the second floor has a height of 3.30 m and an area of 250 m². An assessment of the existing conditions of the building was conducted through an in-depth on-site inspection, considering contemporary construction codes pertaining to seismicity, such as EC-6 and EC-8.

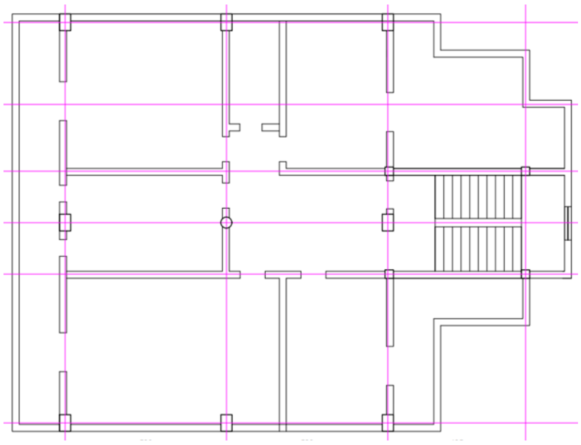

**Figure 3.** Plan view of story 1 of building

## *Material characteristics of structure elements*

The inspection revealed a consistent presence of structural elements across different levels. A noteworthy concern for the building involves the improper integration of the load-bearing skeleton with the non-bearing walls. Notably, the columns themselves exhibit insufficient reinforcement, leading to minor damages primarily observed in the perimeter columns within the protective layer of concrete and the compression-working section.

In the perimeter walls, considerable damage has been observed; however, given that they primarily have a non-load-bearing effect, the damages are reparable. The relatively tall height, especially of the first floor, has resulted in structural damages, but these are also reparable. Lightweight aggregate concrete, characteristic of skeleton structures, has been used for the masonry. For similar constructions in this area, low-grade cement, with a strength rating of 2.5 MPa, has been utilized. The beams and columns are made of low-grade concrete (C20/25) with non-negligible steel reinforcement. Additionally, the protective layer of concrete covering the steel reinforcement is less than 4 cm, and, as evident in the photos below, in some areas, this layer has been damaged. According to information obtained from residents, the foundations are of the isolated type under each column, with a relatively shallow depth of about 80 cm.

**Figure 4.** Facade view of the building

## *The damages incurred due to the earthquake*

Based on observations, it was revealed that the three-story building in Fushë Krujë has incurred light to moderate damages in its load-bearing elements, mainly in some columns of the first-floor skeleton. In general, the columns have suffered minor damages, but their dimensions and the reinforcement placed in them are assessed as insufficient. They measure 60x40cm and are reinforced with 8φ18. Given that the lower floor has a considerable height, the soft-story phenomenon occurs, contributing to the majority of damages on the ground floor. The building can be considered a structure with a load-bearing skeleton, as mentioned earlier, since the columns have a load-bearing effect, while the non-bearing walls do not affect the load-bearing capacity of the building. The perimeter walls, on the other hand, are quite damaged but deemed reparable. They lack seismic bands, and due to the uneven deformation of the skeleton and masonry, various cracks have occurred.

**Figure 5.** Wall and column damage on the first floor of the structure

In the masonry, cracks have been observed in various sections, along with the detachment and separation of non-load-bearing elements from the rest of the structure. High moisture content has been noted in the structure, leading to material degradation in various parts, such as walls and foundations. The material quality is poor, and fractures from shearing forces have been observed in the perimeter walls; however, damages to the walls are predominantly reparable.

**Figure 6.** Damage on perimetral walls of the façade

The examined building has been identified and its current structural bearing capacity has been analyzed. On-site photographs have been taken to describe the current condition of the structure. The current performance of the building has been assessed based on on-site inspection and observation of overall damages to the building, in accordance with modern seismic codes.

## GEOLOGICAL AND SEISMIC CONDITIONS OF THE SITE AND BUILDING MATERIAL PROPERTIES

### *The geological conditions of the site*

For the construction site of the existing structure in question and for the purposes of expertise regarding the load-bearing capacity of the residential building on this site, data obtained from geotechnical and engineering studies in the Fushë-Krujë area have been utilized. In this area, the stratigraphic profile has been established through geological layers characterized by distinct properties and features, represented by five geological layers.

Layer 1 is represented by new clayey-loamy fillings, vegetable brown in color, as well as various materials resulting from the activities of the local residents. The layer has a thickness of approximately 0.8m. Layer 2 is characterized by medium-fine sandy deposits with reddish-brown color and a slight moisture content, ranging from plastic to firm. It contains numerous small pebbles of fluvial origin and is moderately compacted. The layer has a thickness of about 4m. Layer 3 is represented by medium-fine sandy deposits with brown color, containing fragments and gravel of fluvial origin with a brown hue. These deposits are quite moist, in a plastic to soft state, and are slightly compacted. The layer has a thickness of around 0.7m. Layer 4 is represented by medium to clayey sandy deposits with yellowish-brown color. They are moist and in a plastic to firm state, with an average to compacted density. Layer 5 is represented by fluvial silty deposits with a brown color, consisting of small to large particles, occasionally including pebbles. They are well-sorted with little moisture content up to 8.3m and moist below the groundwater level. The silty mass is low and saturated with water, with an average compaction. The layer has a thickness of approximately 9m. Based on the geological structure of the land and for calculation purposes, the soil has been classified as **category C** according to EC-8 or category II according to KTP-89 [2], [11].

### *The seismic conditions of the site*

Drawing on the work "Seismicity Seismotectonics and Seismic Risk Assessment in Albania" (by Aliaj et al., 2010), published by the Academy of Sciences of Albania, as well as data from the Seismological Engineering Study conducted by INGV for the Balkan region, relevant values for maximum ground acceleration have been obtained according to EC-8 for the construction site in question. The seismic parameters necessary for structural control calculations have been determined for the construction site based on the geological structure of the land. In conclusion, after studying the results of the Geotechnical Engineering Study and the Seismological Engineering Study, for seismic risk assessment using the SHAKE 2000 computer program for the construction site of the Object in Kruja, the authors have reached the following conclusions: The construction site in the study is Class C soil according to EC-8 [11].

The main seismic risk parameters for the construction site in rocky soil conditions (Vs, 30 = 760 m/sec) are: for a return period of 475 years, the maximum acceleration PGA = 0.280 g, while the spectral acceleration at a period of 0.2 seconds Sa(0.2s) = 0.480 g, and for a period of 1.0 second Sa(1.0s) = 0.183 g. According to Eurocode 8, the elastic response spectrum for the foundation support layer of the studied structure can be considered as follows: for a 10% probability / 50 years for soil category C according to EC-8, the resulting parameters are:

maximum acceleration ag = 0.278 g and maximum spectral acceleration Se(T) = 1.162 g, S = 1.15, TB = 0.2 s, TC = 0.6 s, and TD = 2.0 s.

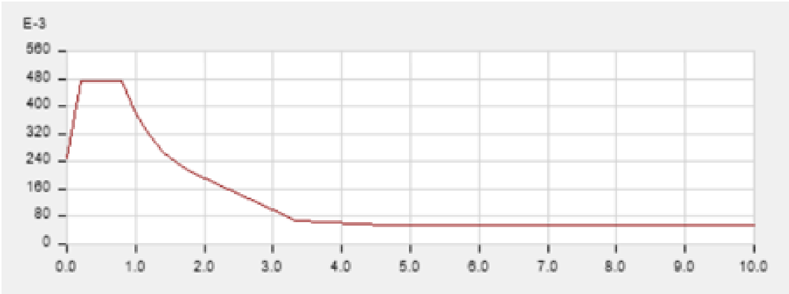


**Figure 7.** Response spectrum for ag=0.28g

It should be noted that according to EC-8, the structure will be calculated for all three performance levels: DL (damage limitation), SD (significant damage), and NC (near collapse). For the DL performance level, the structure must be guaranteed for maximum horizontal acceleration, referring to an earthquake with a return period of 95 years. Whereas, for the SD performance level, the structure must be guaranteed for maximum horizontal acceleration, referring to an earthquake with a return period of 475 years.

## Material properties of the beam-column elements

Regarding the concrete, tests within the structure have been conducted according to SSH EN 12504-2:2012 using a sclerometer. According to them, Class C20/25 concrete has been used for the slabs, beams, and columns. Below are the basic mechanical characteristics for this type of concrete:

Compressive Strength ($f_{ck}$): 20 MPa

Tensile Strength ($f_{ctm}$): 2.5 MPa

Modulus of Elasticity (E): 25,000 MPa

Poisson's Ratio (ν): 0.2

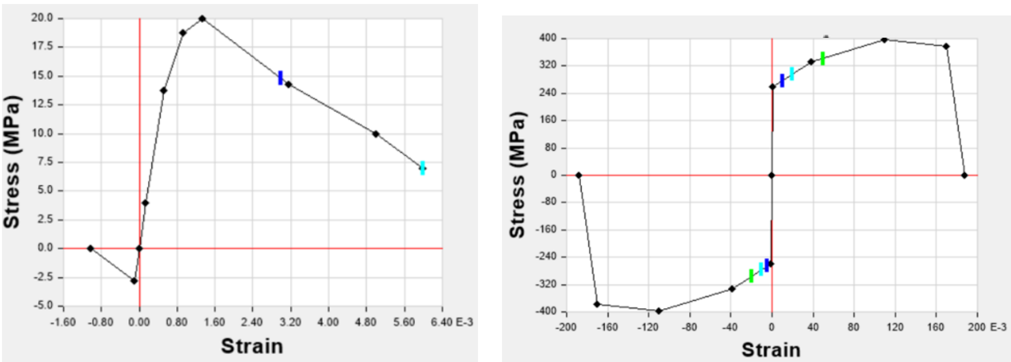


**Figure 8.** Stress-strain graph for concrete(left), steel (right)

The tests for the steel reinforcement used in reinforcing the concrete elements have been conducted according to ISO 16859-1:2015, which outlines the method for determining the dynamic strength of metallic elements in structures without causing destruction. Regarding the steel placed in the stirrups, columns, or slabs, it has a strength of MPa according to KTP-89 or is equivalent to S235 according to EC-3. Below are the basic physical-mechanical characteristics of the steel used:

Yield Strength ($\sigma_y$): 235 MPa

Ultimate Tensile Strength ($\sigma_u$): 360 MPa

Modulus of Elasticity (E): 210,000 MPa Poisson's Ratio (ν): 0.3

## METHODOLOGY OF MATHEMATICAL MODEL AND ANALYSIS

### *Mathematical model of structure*

The mathematical model represents an idealization of a certain number of elements such as shell, frame, link, tendon, and joint. These objects within the computer program are used to represent walls, slabs, columns, beams, and other physical entities. Constructive systems are presented through a three-dimensional network. Highly complex real systems can be represented with simplified mathematical models. Using the finite element analysis method provides highly accurate results regarding external and internal forces. The results include the behavior in flexure as well as out-of-plane behavior. Solving the three-dimensional model allows for maximal inclusion of real conditions in which the structure operates in reality. This approach is known as the finite element method, providing solutions for constrained problems that are particularly suitable for low-rise building cases [13].

Given that the building has the first floor with a significantly greater height of 5.45m compared to the other two floors, which are 3.3m each, and considering that the column dimensions of 60 x 40 cm do not provide sufficient stiffness, the phenomenon of soft story is observed. Below is the computer model of the existing structure built using the ETABS 2018 program.

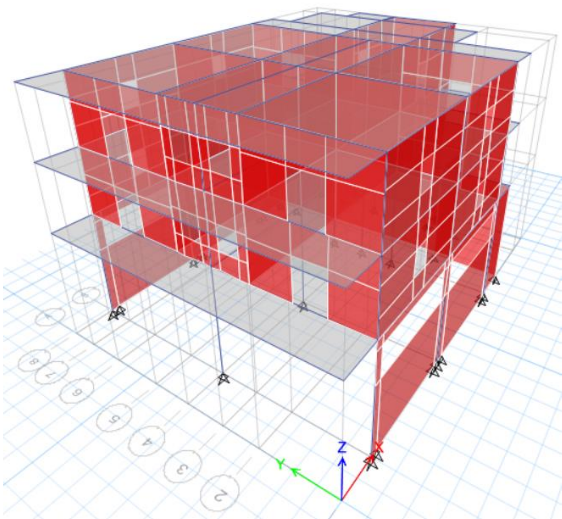


**Figure 9.** Matematical model of the structure(using etabs software)

### *Modal analysis of the structure*

The model has undergone an initial modal analysis. It is observed that the first and second modes of vibration exhibit significant torsional effects. This is attributed to the fact that the columns of the structure have very disproportionate dimensions (60cm x 40cm), and the soft story experiences torsion due to the lack of proper stiffness in the supporting frame. Considerable effects are also contributed by the cantilevers and appendages in the east direction of the structure, which have a relatively significant length. The period of vibrations is also significantly lower than the recommendations of EC-8 for reinforced concrete frame structures. The expected period for masonry-bearing structures according $T=0.1*n_{floors}$ to EC-8 is calculated based on the formula above.

**Table 1.** The data from the modal analysis of the unreinforced building

| Analysis | Mode | Period | Frequency | Cyclic Frequency |
|---|---|---|---|---|
| Modal | 1 | 0.217 s | 4.615 Hz | 28.9943 rad/s |
| Modal | 2 | 0.098 s | 10.23 Hz | 64.2742 rad/s |
| Modal | 3 | 0.072 s | 13.913 Hz | 87.4166 rad/s |
| Modal | 4 | 0.029 s | 34.957 Hz | 219.642 rad/s |
| Modal | 5 | 0.026 s | 37.952 Hz | 238.4618 rad/s |
| Modal | 6 | 0.023 s | 43.269 Hz | 271.8667 rad/s |

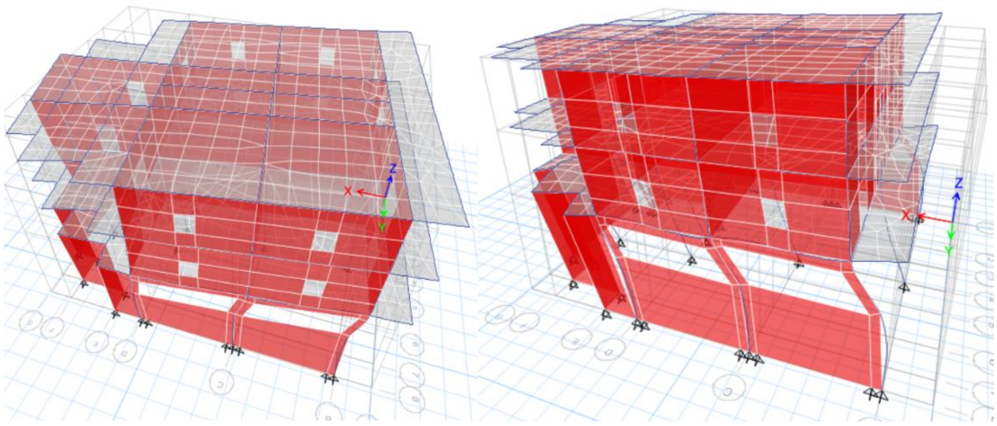

**Figure 10.** First two modes of the structure exhibit significant torsional effects

## *Pushover analysis and spectrum based assessment*

The method used for assessing the structural capacity of the building is the Push-Over analysis, which is a type of Nonlinear Static analysis. In this analysis, seismic input data is applied to the structure by giving it a known displacement at a specific point. This displacement is applied uniformly, and the structure's response is continuously monitored, creating the structural capacity curve until the formation of plastic hinges in beams and columns. By comparing the displacement results obtained from the Response Spectrum analysis (seismic action and vertical loads) with those from the Push-Over analysis (structural capacity), an assessment of the building's condition and its ability to meet safety and serviceability conditions is conducted. Below are the results of the Push-Over analysis.

**Table 2.** The data from the pushover analysis of the unreinforced building

| Direction | Shear force | Weight of structure | Disapl. DL | Displ. SD | Disapl. NC | Disapl. ult |
|---|---|---|---|---|---|---|
| X | 1543 kN | 3784 kN | 1 cm | 1.2 cm | 1.8 cm | 2.4 cm |
| Y | 1607 kN | 3784 kN | 0.9 cm | 1.4 cm | 1.9 cm | 2.7 cm |

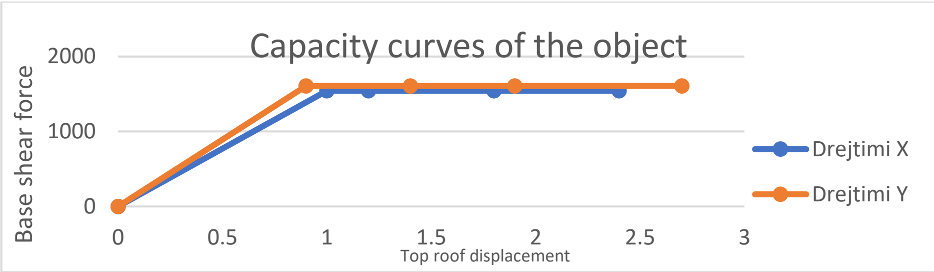


**Figure 11.** Capacity curves of building in x and y directions

Following this analysis, a comparison was conducted between the structural capacity and the earthquake design spectrum for 0.28g, as detailed in the previous chapter. The evaluation is then made through a comparison in the spectral acceleration - spectral displacement (Sa-Sd) format. The comparison graph below illustrates that the structure has surpassed the SD performance level and is now in the NC phase. According to EC-8, this implies significant structural damage, necessitating structural reconstruction. For this seismic level, with a return period of 1/475 years for the zone, the structure should not have reached the SD level, let alone transitioned into the NC phase.

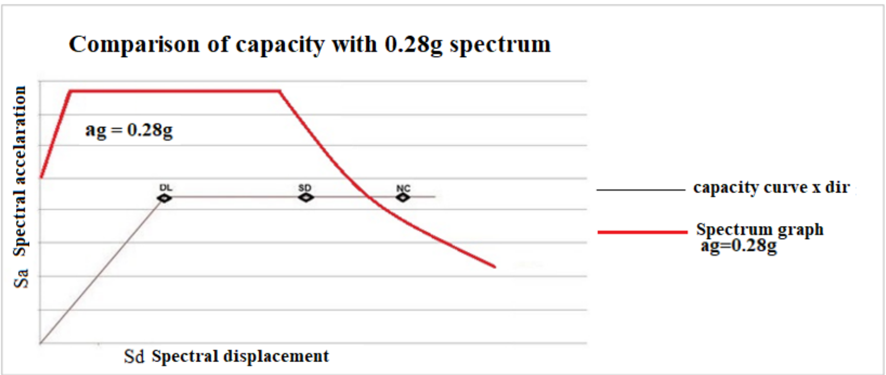


**Figure 12.** Comparison of capacity versus spectrum

## CONCLUSIONS

The analyzed object is a 3-story residential building with a living area of 750 m$^2$, located in Fushë-Krujë, near Krujë. This document presents an in-depth structural expertise for the existing building, which was damaged during the earthquake on November 26, 2019.

From the seismic analysis for the existing structure for an earthquake with a ground acceleration level of 0.28g, corresponding to a return period of 475 years for the area, the structure is designed to the performance level NC Near Collapse or near-collapse phase. According to EC-8, for this level of seismic activity, the structure should not exceed the performance level SD. This implies that the building needs reinforcement to increase its structural capacity and performance.

## FURTHER STUDIES

Three main interventions are proposed by the authors for the reinforcement of the existing structure:

-Installation of Reinforced Concrete Columns: Concrete columns will be planted to form a moment-resisting frame system for the structure.

- Placement of Reinforced Concrete Shear Walls: Concrete shear walls will be positioned along the perimeter of the building to enhance its lateral resistance.

- Strengthening of Foundations: Foundations will be reinforced to provide a robust connection and to increase their load-bearing capacity.

## CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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