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SEISMIC EVALUATION OF THE MINARET OF "CAROL I" ROYAL MOSQUE IN CONSTANȚA, ROMANIA

Eugen LOZINCĂ[1], Matsutaro SEKI[2], Alexandru ALDEA[3]

ABSTRACT

The paper presents the seismic evaluation of the minaret of the "Carol I" Royal Mosque in Constanţa, Romania using the procedure proposed by the Japan Building Disaster Prevention Association. The mosque is a historical monument and a proof of the multicultural community in Constanţa city. It was built in 1910-1913 and it is one of the first constructions using reinforced concrete in Romania. Its circular reinforced concrete minaret is ~40m height, and is probably one of the oldest RC minarets in the world. On site investigation and measurements, old architecture drawings and published non-technical literature allowed the construction of the mosque layout and vertical cross section. The concrete class C12/15 was estimated from documents describing concrete composition and from the practice at that time in Romania. Some data about the reinforcement were found in documents. The over 100 years climatic aggression had a negative impact on the structure, water infiltrations inducing a significant damaging effect on the concrete (cracks and falling down) and on the reinforcement (heavy rusting). The performance of the construction is expressed through the seismic capacity index Is associated to the structural elements. The seismic capacity index is compared to the seismic demand index. The shear capacity represents only 60% of the required value determined for the parameters that characterize the seismic conditions in Constanţa.

Keywords: Cultural Heritage; RC Minaret; Seismic Evaluation; Seismic Index

1. INTRODUCTION

During strong earthquakes, mid-rise reinforced concrete buildings may collapse or overturn. Though, an adequate seismic evaluation and retrofit of vulnerable RC buildings may prevent the structural collapse and the loss of human life and may mitigate the economic losses.

The 1968 Tokachi-oki earthquake is the first major tremor that caused significant damages to reinforced concrete buildings in Japan and raised the concern of the public regarding the seismic safety of RC structures. Therefore, the Ministry of Construction organized a committee to develop a method to evaluate the seismic vulnerability of existing reinforced concrete buildings.

The Japanese standard for seismic evaluation and the guidelines for seismic retrofit of existing RC buildings were initially enforced in 1977. However, it took more than two decades until they were widely applied throughout Japan. Only after the great Hyogo-ken Nanbu earthquake in 1995, the Japanese Diet recognized the importance for urgent enhancement of the seismic resistance of existing buildings and proclaimed a law for seismic strengthening that started nationwide programs for earthquake disaster mitigation (Otani 2000).

In 2001 the Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings was updated. Based on its principles and procedures, Japan Building Disaster Prevention Association (JBDPA) released in 2015 the Standard Evaluation of Existing Reinforced Concrete Chimney.

Although it is not so appealing for research purposes as non-linear analyses, the methods proposed in

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[1] Lecturer, Department of Reinforced Concrete Structures, Technical University of Civil Engineering, Bucharest, Romania, elozinca@utcb.ro

[2] Visiting Research Fellow, Building Research Institute, Tsukuba, Japan, sekimatsutaro@yahoo.co.jp

[3] Professor, Department of Reinforced Concrete Structures, Technical University of Civil Engineering, Bucharest, Romania, alexandru.aldea@utcb.ro

the Japanese standard for seismic evaluation of existing RC buildings follows its long-term objective: ”… to obtain the seismic capacity index using the simplified calculation considering the ultimate strength, the ultimate ductility, the failure mode and the earthquake response quantity. In the process of calculation, the simple method and the engineering judgement are recommended without using the complicated modelling of the buildings.”

The paper presents an application of the Japanese approach for seismic evaluation of reinforced concrete structures to a Romanian case-study: the RC minaret of the "Carol I" Royal Mosque located in Constanţa, south eastern Romania.

The city of Constanţa is exposed to large earthquakes that are potentially expected from Vrancea subcrustal source (maximum credible magnitude Mmax = 8.1) in Romania and from shallow sources in Bulgaria: Dulovo (Mmax = 7.1), Shabla (Mmax = 7.8) and Gorna (Mmax = 7.4).

2. "CAROL I" ROYAL MOSQUE

Located in Constanţa, in South-Eastern Romania, the "Carol I" Royal Mosque (Figure 1) is a historical monument in the architecture category. Its plans were conceived by the Romanian architect Victor Stefanescu who used a mixture of Arabic and Egyptian styles.

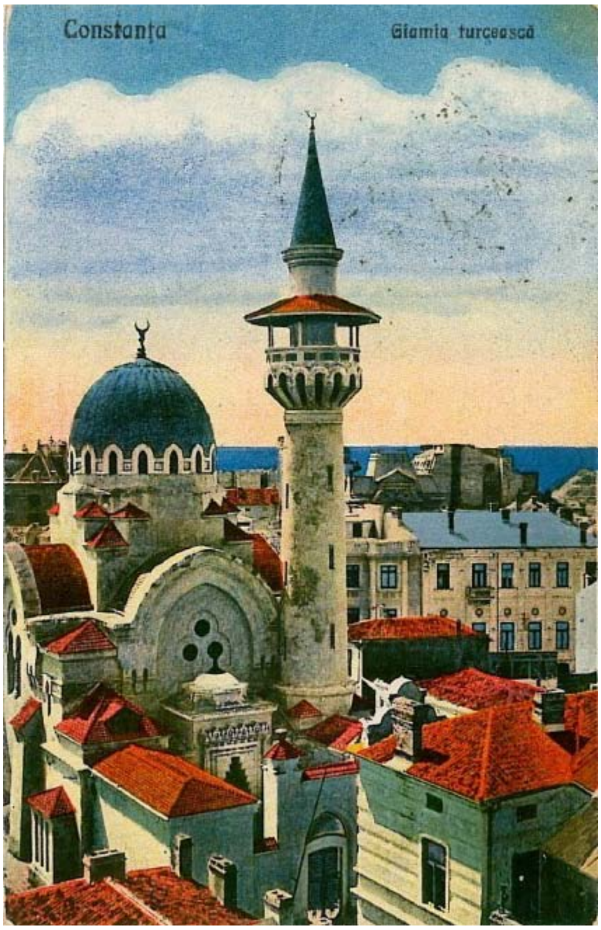

Figure 1. "Carol I" Royal Mosque in old Constanţa city centre (1930's postcard)

"Carol I" Royal Mosque was constructed in between 1910 and 1913 and is one of the first constructions in Romania that includes reinforced concrete structural elements.

The mosque's prayer hall (Figure 2) has a reinforced concrete dome supported by masonry walls and large masonry columns.

The mosque has an ~40m height reinforced concrete minaret, which is probably one of the oldest RC minarets in the world (Figure 1, 2 and 4).

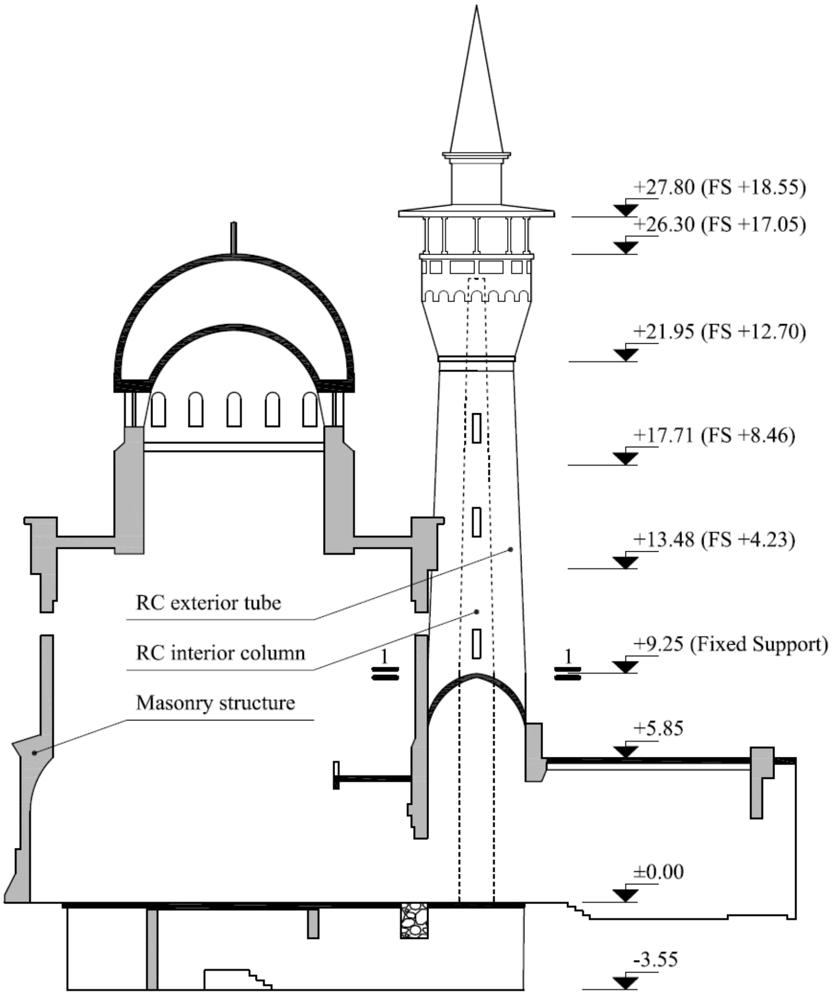

Figure 2. Vertical cross-section of “Carol I” Royal Mosque in Constanţa

The circular shaped RC minaret has a diameter of ~4m at the base and ~3 m at the balcony level. Inside the minaret there is an internal circular reinforced concrete column and an interior spiral staircase going up to the balcony level. The reinforced concrete staircase is fixed at both ends in the outer minaret wall and in the inner tube.

Engineer Gogu Constantinescu (a graduate of the École des Ponts et Chaussées, Bucharest) is often credited for the RC dome and minaret. Constantinescu had a quite wide international popularity, being considered as one of the great inventors of that period (about 400 patents in Europe and US). In the field of constructions, he had important contributions on reinforced concrete and steel structures for buildings, bridges and towers. More details about the mosque are given in Aldea et al., 2017, 2018.

Several major and medium size earthquakes originating from the subcrustal Vrancea seismic source in Romania hit the mosque: 1940 (M_W=7.7), 1977 (M_W=7.5), 1986 (M_W=7.2), 1990 (M_W=6.9 and 6.4) and 2004 (M_W=6.0). The mosque did not suffer any significant damage. However, the long-term climatic aggression (strong directional winds from the Black Sea, shore humidity) had a negative impact on the structural materials (both masonry and reinforced concrete), and degradations were repeatedly reported. Thus, the mosque and its safety are threatened by seismic, wind and climatic actions and construction materials degradation.

3. JAPANESE METHODOLOGY FOR SEISMIC EVALUATION

According to the Japanese procedure, the seismic evaluation of an existing reinforced concrete chimney aims to check if the effective seismic capacity is higher than the required seismic capacity (seismic demand).

3.1 Seismic demand

The seismic demand is evaluated through the required seismic capacity I_{so}-index:

$$I_{so} = E_s \cdot Z \cdot G \cdot U_o \quad (1)$$

where E_s is the required basic seismic capacity index based on the country's seismic intensity, Z is the zone index depending on the location seismicity, G is the soil factor that accounts for topography and amplification of the seismic motion and U_o is the usage (importance) factor.

According to Romanian seismic design code P100-1/2013, the design ground acceleration for Constanţa city is $a_g = 0.2g$ (life safety limit state, 225 yr. mean return period, i.e. 20% exceedance probability in 50 yr.) and the normalized design acceleration spectrum shown in Figure 3.

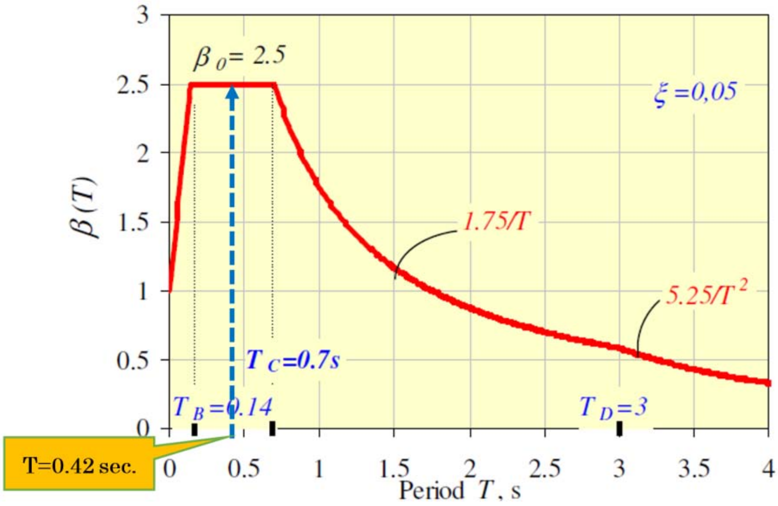

Figure 3. Normalized design acceleration spectrum for Constanţa city, Romania (P100-1/2013)

For the fundamental period of $T_1 = 0.42$ sec. estimated from ambient vibration tests (Aldea et al., 2017, 2018), the dynamic amplification coefficient is $\beta(T_1) = 2.50$.
Considering its historical and architectural value, the over 100 years old Minaret should behave elastically in order to exhibit very limited damages to strong earthquakes. Therefore, the behavior factor should be taken as $q = 1.0$.
So, the required basic seismic capacity index defined as the design acceleration normalized by the gravitational acceleration is equal with:

$$E_s = S_d(T) / g = (a_g/g) \cdot \beta(T) / q = 0.5 \quad (2)$$

Considering the topography (flat land) and the soil characteristics for the location of the Minaret, both the zone index Z and the soil factor G are equal with 1.0.
Since the Great Mosque of Constanţa belongs to the Romanian national patrimony, the usage (importance) factor is $U_o = 1.20$.
Finally, the seismic demand index computed by equation (1) is equal with $I_{so} = 0.6$.

3.2 Seismic capacity

Seismic capacity is numerically evaluated by the I_s-Index defined in the Standard as:

$$I_s = E_o \cdot S_D \cdot T \quad (3)$$

where E_o is a basic structural seismic capacity index, S_D is a factor that accounts for structural irregularity and T is the time index that considers the time deterioration of the original performance. Higher values of I_s index shows a better seismic performance of the evaluated structure.

The basic structural seismic capacity index is computed as the product of the strength index C_T expressed in terms of story shear coefficient and the ductility index F that depends on the failure mode and the sectional properties such as bar arrangement, member's geometric size etc.

$$E_o = C_T \cdot F \tag{4}$$

The strength index id further defined as the minimum value between the bending capacity index C_{BM} and the shear capacity index C_{BS}:

$$C_T = \min (C_{BM}, C_{BS}) \tag{5}$$

$$C_{BM} = M_{u,i} / [W \cdot H_G \cdot (1 - H_i / H)] \tag{6}$$

$$C_{BS} = Q_{su,i} / [W \cdot (1 - 0.7 \cdot H_i / H)] \tag{7}$$

where $M_{u,i}$ and $Q_{su,i}$ are the bending and shear capacity at the "i" level, W is the total weight of the building, H_i is the height at the "i" level and H is the total height of the structure.

The ductility index varies from F = 1.0 for shear failure type ($C_{BS} / C_{BM} < 1.0$) to F = 2.0 for flexural failure when $C_{BS} / C_{BM} \geq 1.3$. For $1.0 < C_{BS} / C_{BM} < 1.3$, the ductility index should be determined by linear interpolation.

The RC minaret of the “Carol I” Royal Mosque in Constanţa has a structural system that is quite similar to the structure of an RC industrial chimney. Nevertheless, in contrast to common RC chimney, besides the exterior reinforced concrete tube, the minaret has an additional interior RC circular column and an interior spiral staircase up to the balcony level.

Thus, the simplified Japanese evaluation method was performed considering two independent “chimneys” linked by the monolithic RC staircase.

Up to 9 m from the ground level, the lateral movement of the minaret is restricted because it is contained within the masonry structure of the mosque. So, the seismic evaluation assumed that the RC minaret is free to experience horizontal vibrations only above the level +9.25, Figure 4.

Figure 4. The minaret of "Carol I" Royal Mosque in Constanţa (2017 photo)

In the first decades of the 20th century the RC minaret experienced a rapid degradation of the concrete and corrosion of the rebars due to the exposure to sea winds. Therefore, at the end of the 1960's, an exterior reinforced concrete layer was casted on all over the minaret height.

The diameter of the original RC minaret varies from 3.8 m at the base up to 2.8 m below the balcony. The thickness of the initial outer tube ranges from 20 cm at the base up to 15 cm at the top of the minaret.

The reinforcement consists of a system of 18mm thick vertical bars placed at the middle of the tube thickness, spaced at 20cm at the base up to 15cm at the top, with 8mm thick circular stirrups at about 20 cm distance. The 7-8 cm thick outer RC jacket is reinforced with a mesh of 12mm thick vertical and 10mm thick horizontal rebars spaced at about 25 cm distance.

The diameter of the interior column decreases continuously from 1.4 m at the base to 0.65 m at the balcony level. The interior column is reinforced with thin rebars: 18 to 20 vertical bars with 8mm diameter and spiral stirrups with 6mm diameter.

The quality of the concrete and the reinforcement details were investigated by non-destructive limited tests. Since it was not allowed to extract rebars from the existing structure, the seismic evaluation considered the mechanical characteristics of the steel commonly used in the periods when the mosque was erected and then jacketed.

Figure 5 shows the geometry, reinforcement details and the mechanical properties of the concrete and steel rebars for the bottom section in the fixed support of the RC minaret of the mosque.

The Tables 1, 2, 3 and 4 show the main numerical results provided by the simplified Japanese method for evaluating the seismic capacity index in the horizontal levels represented in Figure 2. Level +9.25 was assumed as fixed support of the minaret because up to this level its lateral movement is restricted by the masonry structure of the mosque.

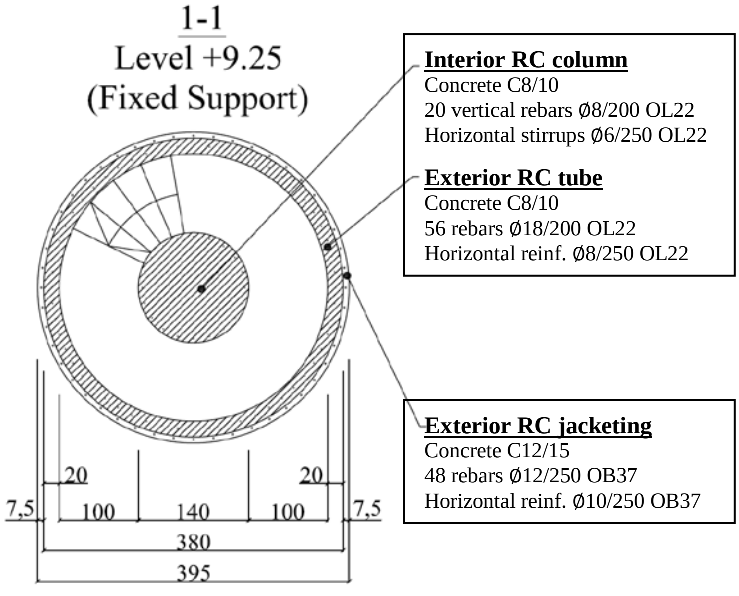

Figure 5. Cross-section of the RC minaret at level +9.25m

Since the contribution of the interior column to the flexural strength is very small, the bending capacity index was determined only for the exterior RC jacketed tube, while the shear capacity index considered both contributions of the outer tube and the interior circular column.

According to Japanese Standard Evaluation of Existing Reinforced Concrete Chimney (JBDPA, 2015) the flexural capacity of the outer tube of the minaret should be computed as:

$$M_u=2\cdot t\cdot r^2\cdot \sin(\theta_D)\cdot(2\sigma_y\cdot p_g + 0.85F_C)/10^6 \quad \text{(kNm)} \tag{8}$$

$$\theta_D=[1 / (2\sigma_y\cdot p_g + 0.85F_c)]\cdot[N/(2t\cdot r) + \pi\cdot\sigma_y\cdot p_g] \quad \text{(rad.)} \tag{9}$$

where t is the wall thickness, r is the outside radius of the cross-section, σ_y = 220 MPa is the steel yielding stress, p_g is the longitudinal reinforcement ratio, F_C = 16 MPa is the compressive strength of the concrete and N is the axial force acting in the respective horizontal section.

Table 1. Ultimate flexural strength (M_u) of the outer RC jacketed tube.

Level	**A (m^2)**	**r (mm)**	**t (mm)**	**a_g (mm^2)**	**p_g**	**N (kN)**	**θ_D (rad)**	**M_u (kNm)**
+21.95	2.02	2948	235	14751	0.0073	1493	0.364	24445
+17.71	2.44	3278	255	16221	0.0066	2073	0.352	31125
+13.48	2.9	3618	275	17690	0.0061	2733	0.343	39435
+9.25	3.17	3938	275	19668	0.0062	3422	0.359	48934

According to Japanese standard (JBDPA, 2015) the shear capacity of the outer tube of the minaret should be computed as:

$$Q_{su} = \kappa \cdot p_s \cdot {}_w f_t \cdot A \qquad (10)$$

where κ is the ratio of the average shear stress to the maximum shear stress (since there are only small openings κ = 0.5), p_s is the transverse reinforcement ratio, ${}_w f_t$ = 280 MPa is the transverse reinforcement strength and A is the cylinder cross-sectional area in the calculated cross section.

Table 2. Ultimate shear strength (Q_{su}) of the outer RC jacketed tube.

Level	**A (m^2)**	**t (mm)**	**a_{s1} (mm2)**	**p_s**	**Q_{su} (kN)**
+21.95	2.02	235	129	0.0022	621
+17.71	2.44	255	129	0.0020	691
+13.48	2.9	275	129	0.0019	762
+9.25	3.17	275	129	0.0019	833

The ultimate shear strength of the interior circular RC column was computed with equation A1.1-2 provided by the Japanese “Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings”, (JBDPA 1977, revised in 1990 and 2001).

In Table 3 a_t is the area and p_t is the ratio of the tensile longitudinal reinforcement, N is the axial force and σ_0 is the compressive stress in the calculated cross-section of the interior RC column and j represents the distance between centroids of tension and compression forces (default value is 0.8D, where D is the diameter of the column).

Table 3. Ultimate shear strength (Q_{su}) of the interior RC circular column.

Level	**A (m^2)**	**t (mm)**	**a_{s1} (mm^2)**	**p_s (%)**	**a_t (mm^2)**	**p_t (%)**	**N (kN)**	**σ_0 (MPa)**	**j (mm)**	**Q_{su} (kN)**
+21.95	0.50	708	57	0.032	251	0.0500	117	0.23	566	202
+17.71	0.79	886	57	0.026	251	0.0320	315	0.40	709	297
+13.48	1.13	1063	57	0.021	251	0.0222	558	0.49	850	402
+9.25	1.54	1240	57	0.018	301	0.0196	827	0.54	992	503

Considering that the flexural capacity of the minaret is provided only by the outer RC jacketed tube, while the shear capacity represents the summation of the shear strength of both the exterior tube and the interior RC circular column, the bending capacity index C_{BM} and the shear capacity index C_{BS} shows the following values:

Table 4. Strength index (C_T) and ductility index (F)

Level	H_i (m)	W_i (kN)	M_u (kNm)	C_{BM}	Q_{su} (kN)	C_{BS}	C_{BS}/C_{BM}	F	Failure mode
+21.95	12.7	1493	24445	2.97	823	0.83	0.28	1.00	Shear
+17.71	8.46	2073	31125	2.08	988	0.61	0.29	1.00	Shear
+13.48	4.23	2733	39435	1.62	1164	0.48	0.30	1.00	Shear
+9.25	0.00	3422	48934	1.35	1336	0.39	0.29	1.00	Shear

It can be easily seen that the bending capacity of the minaret is much larger than required, but, up to 18m above the ground level, the shear capacity is less than required. Thus, the RC minaret is highly susceptible to a brittle shear failure. The main reason of the vulnerability is the insufficient horizontal reinforcement.

On the other hand, the ultimate flexural strength is much higher than the shear strength. Therefore, the smallest value of 1.00 should be assigned to the ductility index F.

Since the RC minaret shows no structural irregularity, $S_D = 1.0$.

The time index T is determined as the average value assigned to 5 different deterioration criteria regarding: the presence and opening values of the cracks; the cover concrete and rusting of rebars; the carbonation of the concrete; the deterioration of the concrete strength and the deterioration of the lining material. Some cracks and rusted rebars were observed during the on-site inspection. Therefore, the time index was computed as $T = (0.9+0.9+1+1+1)/5 = 0.96$.

Finally, the seismic capacity index is:

Table 5. Seismic capacity index (I_S)

Level	C_T	F	E_o	S_D	T	I_S	I_S/I_{SO}
+21.95	0.83	1.00	0.83	1.00	0.96	0.80	1.33
+17.71	0.61	1.00	0.61	1.00	0.96	0.59	0.98
+13.48	0.48	1.00	0.48	1.00	0.96	0.46	0.77
+9.25	0.39	1.00	0.39	1.00	0.96	0.37	0.62

Above the level +9.25, where the minaret is laterally fixed by the masonry structure of the mosque, the shear capacity represents only 60% of the required value determined for the parameters that characterize the seismic conditions in Constanţa.

4. CONCLUSIONS

The “Carol I” Royal Mosque represents one of the most important historical buildings in Constanţa that belongs to the Romanian national patrimony. During its lifetime, the mosque was exposed to a long term climatic aggression and to several major and moderate Vrancea subcrustal earthquakes and several reparations were executed in 1925, 1957 and 1993 (Pauleanu and Coman, 2010).

Following the Japanese evaluation procedure for existing reinforced concrete chimneys, the RC minaret of the mosque was analyzed, and it was found that its seismic capacity is lower than required by the seismic parameters defined for Constanța in the Romanian seismic design code P100-1/2013.

Following the Romanian seismic evaluation code P100-3/2008, the seismic risk class of an existing building is established based on the values of three different factors resulting from three evaluation criteria. In Aldea et al., 2018, the assessment of existing damage state induced by previous earthquakes and/or other actions (index R2) is presented for both the prayer hall and for the minaret. The in-situ inspections of the mosque revealed significant structural damage reducing its strength to both gravity and lateral loads and also the overall lateral stiffness. Considering the minaret as an independent structure and taking into account only the damage degree index R2, the minaret structure may be ranked in the seismic class RsIII (associated to the buildings that after the design level earthquake might suffer some structural damage not affecting the overall structural safety). The other two Romanian evaluation procedures are under study.

Considering the results of the seismic evaluation of the minaret through the Japanese standard (JBDPA, 2015), an adequate strengthening method should be applied in order to increase its shear capacity. Smart retrofitting solutions like FRP wrapping or steel band plate should be considered in order to reduce the aesthetic impact on the historical building.

5. ACKNOWLEDGMENTS

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