BEHAVIOR OF DWELLINGS DURING STRONG EARTHQUAKES IN ROMANIA

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ABSTRACT :

The paper presents a short description of the seismotectonics and seismicity of Romania, together with the main features of the strong earthquakes that had affected its territory, in order to understand the behavior of different residential buildings from several parts of the country. The behavior of dwellings during the November 10, 1940 and March 4, 1977 earthquakes is briefly presented. Some other three seismic events occurred in Romania after 1977 (August 30/31, 1986, May 30 and 31, 1990). The frequent occurrence of strong earthquakes in Romania led to a situation in which an important part of the building stock was overloaded and/or damaged several times and, in the absence of appropriate rehabilitation works, it has become more vulnerable than initially. Brief information on the evolution of the seismic legislation and final remarks complete the paper.

KEYWORDS: dwelling, damage, soft and weak story, earthquake, Bucharest, Romania

1.SEISMOTECTONICS AND SEISMICITY OF ROMANIA

Romania is one of Europe's most seismically active regions, together with other Balkan and Mediterranean countries (Bulgaria, Turkey, Greece, former Yugoslavia and Italy). A short description of the seismotectonics and seismicity of Romania is as follows (Pomonis and others, 1990). Romania has a surface area of 237,500 km^2. The most important geographical feature of the country is represented by the Carpathian Mountains that form a curve that separates the country into two distinct geographical and cultural zones. The mountains spread from the center of the Northern border of the country southward for 280km, at which point a sudden turn of almost 90 degrees occurs due to the collision between the African and Eurasian plates. As a result, the rest of the Carpathians spreads westwards for a further 320 km, almost parallel to the Bulgarian borders and the flow of the Danube river. These two parts of the mountain chain are called Oriental and Meridional Carpathians. The Carpathian bow is one of the most striking features of the Alpine Chain, the seismicity of Romania being related to this spectacular geomorphological feature.

The Oriental Carpathians with their northwestern extension in the Tatra mountains form the border between two distinct parts of the large Eurasian Plate. These are the Inter-Alpine subplate and the East European plate (covering Moldavia, Ukraine, Russia and Siberia). The Inter-Alpine subplate is further divided in two distinct litospheric formations within Romania’s territory that are separated by the Carpathian Mountains. In the Southeast of the mountains lies the Black Sea subplate (also called the Moesic subplate), that moves towards Northwest, subsiding underneath the Carpathians. In the North and West, the rest of the country is covered by the largely aseismic Transylvanian plateau. As a result of this complex tectonic formation, considerable crustal movements are observed in Romania. In the zone of the Oriental Carpathians a crustal uplifting of more than 5 mm per year is occurring, while a much smaller displacement is observed along the Meridional Carpathians. In Transylvania a subsidence of about 2 mm per year is occurring in the zone parallel to the Oriental Carpathians, a subsidence of the same order being registered around the Black Sea coast. Because of these crustal movements, the seismic activity of Romania is considerable, having (conventionally) nine distinct seismic regions. Among these, the most important are: Vrancea, Fagaras, Banat and Dobrogea. Vrancea is by far the most seismically active zone of Romania, placed around the curvature of the Carpathians, where the submerging of the Moesic subplate takes place. *Subcrustal earthquakes* of moderate to large magnitudes ($6 < M_W < 7.5$), with depth of focus ranging between 60 and 170 km, occurred quite frequently. A few shallow focus earthquakes of smaller magnitude ($M_W < 5.5$) occur within this zone, especially towards its southern part. Another contribution to the seismic hazard of Romania is the *crustal contribution* that comes from various, less active and less intensive, shallow seismogenic zones that are distributed over the entire territory of the country. In terms of earthquake risk, the second most important seismicity zone in Romania is the Fagaras zone placed in the Meridional Carpathians, where the earthquakes are of shallow focus. The seismic risk of this zone should not be underestimated, as shallow earthquakes of M_W = 6÷6.5 occurring near towns have a considerable potential of destruction. In the Banat region, situated in the S-W of the country, shallow earthquakes occurred on July 12 (M_S=5.7), July 18 (M_S=5.6) and on December 2 (M_S=5.6), 1991, and produced significant damage (Figure 1). In conclusion, the seismicity of Romania is mainly due to activity from within the Vrancea region that delivers in the average, per century, more than 95% of the entire seismic energy for the country. This source zone has direct influence over about half the territory of Romania, producing high intensity earthquakes. The upper limit of magnitudes for Vrancea earthquakes is considered to be $M_W \approx 8.0$. Taking into account all the aspects above mentioned, the design and the behavior of buildings placed in seismic zones is of major importance for Romania.

Date	Latitude / Longitude	Focus depth (km)	M_{G-R}	M_W
November 10, 1940	45.80° / 26.70°	133	7.4	7.8
March 4, 1977	45.78° / 26.78°	93	7.2	7.5
August 30/31,1986	45.53° / 26.47°	133	7.0	7.2
May 30, 1990	45.82° / 26.90°	91	6.7	7.0
May 31, 1990	45.83° / 26.89°	79	6.1	6.3

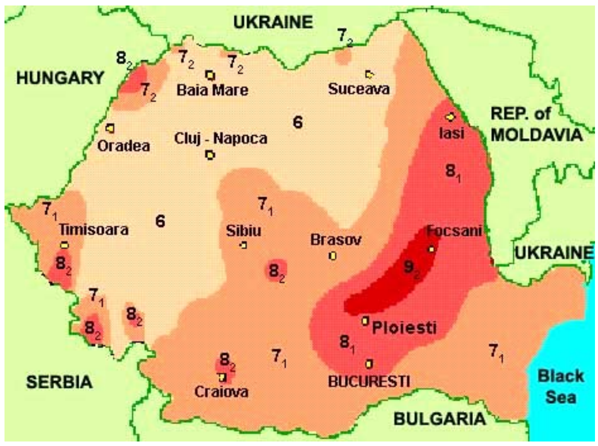

Figure 1. Recent strong earthquakes and the seismic zonation map (in terms of intensities) of Romania

2. MAIN FEATURES OF STRONG EARTHQUAKES IN ROMANIA

During the last 68 years, Romania was struck by two destructive intermediate-depth earthquakes which occurred in the Vrancea region on November 10, 1940 (M_{G-R} =7.4) and March 4, 1977 (M_{G-R} =7.2). These two were followed by other three strong ground motions, with the same focus, on August 30, 1986 (M_{G-R} =7.0), May 30, 1990 (M_{G-R} =6.7) and May 31, 1990 (M_{G-R} =6.1).

2.1 March 4, 1977 Vrancea earthquake

The first strong motion recorded in Romania was the triaxial accelerogram obtained on a 1967 SMAC-B type strong motion accelerograph during the March 4, 1977 Vrancea event, in the soft soil condition of Bucharest. The peak ground acceleration values in the N-S, E-W and vertical directions were 0.20g (PGA=194.9 cm/s^2), 0.16g and 0.10g, respectively. A glance at the record shows that the long period components were predominant, aspect that surprised the engineering community of Romania, although engineers were acquainted with the code proposal written by engs. Emilian Titaru and Alexandru Cismigiu at the 2WCEE (Japan). So, one can consider as birth date of the instrumental earthquake engineering in Romania the date of March 4, 1977.It is interesting to note that the shape of the spectral accelerations was very different of that generally assumed in the code in force. It must be mentioned that the elastic spectra shape had been imported from the Soviet code SN-8-57, characterized by a maximum dynamic amplification factor β_0 =3.0 and a corner period of response spectra T_C=0.3s, which, at its turn, corresponded to the 1940 El Centro earthquake spectra. In order to compare the acceleration response spectrum of the March 4, 1977 earthquake N-S component with the acceleration response spectrum of the N-S component of the 1940 El Centro earthquake, the latter was normalized to the same peak magnitude and plotted on the same diagram. The shapes of the spectral accelerations of these two earthquakes are very much different from each other. *The highest values of periods occurred in the range of 1.0...1.6 s for the N-S component, and of 0.7...1.2 s for the E-W component*. Taking into account the above-mentioned values of the dominant periods, it was to be expected that the damage should occur especially for the flexible buildings, having fundamental eigenperiods of vibration of about 1 s or more. With this information in mind, one can make a pertinent characterization of the behavior of residential buildings and dwellings during earthquakes in Romania.

2.2 August 30/31, 1986 Vrancea earthquake

During the night of 30 to 31 August 1986, Romania was shaken by another earthquake originating in the Vrancea seismogenic zone. This earthquake affected with high intensities extensive areas. The maximum acceleration recorded during this seismic event was close to 0.3g (in fact, the highest *PGA* value was recorded in Focsani, a town located in the nearest vicinity of the instrumental epicenter). The *PGA* values in Bucharest ranged between 0.06 g and 0.16 g (for the N-S component) and between 0.04g and 0.11g (for the E-W component), with the predominant periods ranging between 0.7 and 1.1 seconds. There were considerable differences in the spectral contents of the motion at different sites. The magnitude of this earthquake was M_W =7.3 (M_S ≅6.8, M_{G-R} =6.9, m_b =6.5 to 6.6). The 1986 INCERC record at the same location as in 1977 had *PGA* values of 0.10g (E-W component) and 0.09g (N-S component), with predominant period of 1.1 s. This supports the idea that intermediate depth earthquakes tend to produce longer predominant periods when their magnitude increases.

2.3 May 30 and 31, 1990 Vrancea earthquakes

During the May 1990 earthquakes at least 29 seismic instruments were triggered in various towns, especially in the East and South of the Carpathians, and 9 seismic instruments recorded the motion in different locations in Bucharest. Firstly, it must be mentioned that 5 stations recorded *PGA* values larger than 0.20g in a wide area (maximum value in Campina equal to 0.26g). A variety of *PGA* values between 0.07g and 0.14g were reported during the main shock in Bucharest. Several new lessons seemed to emerge with the first information obtained from the 1990 accelerograms in Bucharest. Many records of the main shock on the E-W direction were stronger than on the N-S components (opposite to the previous two seismic events). The second important remark was that the predominant periods were, this time, much shorter. The characteristics of the strong motions recorded in *Bucharest* during the 1977, 1986 and 1990 Vrancea earthquakes are summarized as follows (Pomonis, 1990):

- *PGA* (cm/s^2): 215 (1977); 60 to 160 (1986); 70 to 140 (1990);
- Predominant period (s): 0.9 and 1.5 s (1977); 0.7 to 1.1 s (1986); 0.25 s (1990);
- Predominant component: N-S (1977); N-S (1986); E-W (1990).

3. EXISTING CATEGORIES OF DWELLINGS

In what concerns the residential building typology, the building types are divided into the following main categories, according to their structural systems: *load-bearing masonry buildings* (compacted clay, adobe, stone masonry low-rise brick masonry and mid-rise apartment buildings) and *reinforced concrete buildings* (non-seismic old reinforced concrete frames with, or without, shear walls, large panel reinforced concrete structures and box-unit reinforced concrete structures). Due to the limitation of the number of pages a description of the characteristics of each structural system above mentioned was not possible.

4. DWELLINGS BUILT IN THE PERIOD BEFORE 1940

Until November 10, 1940, the last and probably the highest intensity subcrustal Vrancea earthquake mentioned in the history of Romania as having produced important damage to dwellings has occurred at noon on October 26, 1802, corresponding to a magnitude M_W = 8.0±0.2. Since, this earthquake is known as the "*Great Earthquake*". As the other earthquakes that have occurred in the period between 1802-1940 have caused limited damage, knowledge in the field of earthquake engineering was absent during the period before 1940 for the Romanian civil engineers. As a result, the seismic action was not taken into account in the design process of constructions. The most reasonable explanation could be that no strong earthquake had occurred in recent past, therefore no official technical requirements together with scientific concerns in seismic design existed. Therefore, when on November 10, 1940 a very strong earthquake has devastated an important area of the country, especially the capital city Bucharest, there was generally great surprise. In Romania, before 1900, most of the buildings were of traditional shape, with load-bearing brick walls and wood floors, without any provision for horizontal forces, except for the usual wall-ties and floor-joists anchors. After 1910, the use of reinforced concrete in floors and frames assured a better behavior against horizontal forces, but only the effect of wind was sometimes taken into consideration. Generally, the presence of interior walls was considered as providing sufficient lateral bracing (Beles, 1968). In the period between the two world wars, the most powerful influence over the structural design engineers was held by the German technical legislation. The period between 1920÷1940 was characterized by an important economic and urban development of large towns in Romania, Bucharest having a prominent place. Thus an important number of reinforced concrete residential buildings, as well as some of the most representative constructions in Bucharest, were achieved. All these buildings were conceived, analyzed, and designed, by private design entities, which used very "prompt" designing methods. A general characteristic of this period is that the design of buildings was carried out almost exclusively for gravity loads. Another aspect that must be considered is related to the fact that the structural designers had rudimentary knowledge of structural analysis and limited knowledge of reinforced concrete theory and of proportioning of structural elements. The strongest earthquake (from the seismological point of view) of the twentieth century occurred on November 10, 1940 (M_S=7.4). This earthquake has severely damaged many residential buildings in Bucharest, including reinforced concrete apartment buildings. It also caused the collapse of one of the highest multi-story reinforced concrete residential buildings, known as "Carlton" building. The important damage produced by this seismic event to many buildings, together with the disaster represented by the collapse of the "Carlton" building, put to evidence, for the first time in modern Romania, the problem of building safety to seismic actions and the mode of preparedness against earthquake effects (Beles, 1941). As a conclusion, for the period that we are discussing about, the achievement of buildings depended on the capability and responsibility of the designers, as well as of the entrepreneurs. For this reason, buildings of unequal quality resulted, from the point of view of the general conception, of the structural design and of the execution.

5. BEHAVIOR OF DWELLINGS DURING THE NOVEMBER 10, 1940 EARTHQUAKE

Damage to buildings is summarized in a paper written in the German publication "Die Bautechnik" (Niculescu, 1941). The November 10, 1940 earthquake was reported as having the intensity 9 on the Mercalli-Cancani -Sieberg scale in Bucharest, the strong ground shaking lasting for 42 seconds. No instrumental readings were obtained. In the epicentral region the dwellings from some villages were totally destroyed. Extremely severe damage was noticed in the two towns, Panciu and Focsani, situated in the neighborhood of the epicenter (Figure 2). Many roofs, chimneys and walls of the buildings were damaged. Apparently very few roofs collapsed, but many were displaced laterally, as much as 20 cm. Gable walls supported on columns were displaced up to 18 cm. Vertical and horizontal cracks and evidence of torsion were observed in chimneys. More chimney damage was observed in buildings with high-pitched roofs. This may have been due to the fact that chimneys on buildings of this type were higher, and consequently more flexible. There was also some damage to buildings as a result of foundation settlement. Difference in damage between adjacent buildings was attributed to the variation of soil conditions throughout the city.

Figure 2. Damage of dwellings in Panciu and Adjud towns, 1940 (Niculescu, 1941).

Most of the residential buildings situated in the center of Bucharest were built between 1910 and 1940. They are multistory load-bearing concrete frame buildings, typically 8 to 12 stories high. It must be mentioned that reinforced concrete was introduced in Bucharest only after 1910. The first story was generally higher than the rest and was almost void of walls in order to accommodate stores and other non-residential facilities. In the upper stories, infill walls and partitions were used liberally to provide enclosure for apartment space and to behave as lateral bracing against wind action. As a result, the structure was characterized by laterally stiff upper stories resting on relatively flexible columns at the ground level. Because they were commonly built adjacent to each other, and more or less conform to the irregular patterns of the city blocks, the end and corner units tend to be non-uniform in layout. In his paper, Niculescu presents observations of building damage caused by the earthquake of November 10, 1940. The worst disaster occurred as a result of the collapse of the (then) relatively recent Carlton building (Figure 3), a 47 m tall reinforced concrete structure, which caused a loss of 130 lives. In Bucharest, other buildings of reinforced concrete were also damaged, and 28 of them, which were then weakened, collapsed during the March 4, 1977 earthquake.

The essential cause of the complete collapse of the Carlton building was the structural conception on which the design of the reinforced concrete frames had been based. As there were shops at the ground floor, in order to get as big shop-windows as possible, some of the columns were reduced to transversal reinforced concrete walls only 22 cm in width, but 200 cm in length (Beles, 1960). Among other causes that may have contributed to the collapse were the unfavorable position of the 47 m high corner tower with respect to the direction of the earthquake motion, the possible amplification of earthquake effects due to the proximity of the foundation to the water table, the location of the building at the end of a row of tall buildings and the cantilevering of the first floor theater seats from the columns. Professor Cristea Niculescu was the first one who brought into discussion the *resonance phenomenon* in connection with the total collapse of this building.

6. BEHAVIOR OF DWELLINGS DURING THE MARCH 4, 1977 EARTHQUAKE

This earthquake has furnished a particularly large amount of information of great importance for Romania and for general knowledge in the field of seismology and earthquake engineering.

In the small village Vrancioaia, two kilometers West of the epicenter, the effects of strong ground shaking were less severe; superficial cracking of adobe/wood walls in one-story dwellings (Figure 4,a) was typical of observed damage. In the towns of Focsani and Buzau, located between the epicentral area and Bucharest, unreinforced masonry walls in low-rise buildings partially or totally collapsed, and movement between structural elements and adjacent masonry in-fill walls was observed in recently then constructed and engineered buildings. In the town of Galati, to the Southeast of the epicenter, about twenty older dwellings were seriously damaged (none collapsed) and numerous others sustained slight or moderate damage. In several small towns to the North of Ploiesti, at least one several-hundred-year-old building collapsed and other unreinforced masonry-wall buildings were heavily damaged. In the towns of Craiova, Alexandria and Zimnicea that are located to the West and Southwest of Bucharest, unreinforced masonry walls in low-rise buildings reportedly collapsed partially or totally. By contrast, the effects of strong ground shaking were slight in Brasov and Bacau, to the West and North of the epicenter respectively. In Bucharest the degree of damage undergone by buildings, especially by blocks of flats, ranged from apparently no damage, or a slight one, to heavy damage and even collapse.

Figure 3. “Carlton” building. General view before and after the November 10, 1940 earthquake.

The heaviest consequences on old buildings have been recorded in Bucharest, where 28 apartment buildings located in the central area have totally or partially collapsed. 20 of them were high-rise buildings provided with reinforced concrete structural members. The 1940 earthquake had heavily affected most of these buildings, so that these didn’t dispose any more of the necessary resistance capacity for a second strong earthquake. Most of the buildings that collapsed have been located at street corners. This aspect confirmed the unfavorable effects of overall torsion oscillations, of whipping behavior and of shocks transmitted by adjacent buildings. The main causes of the collapse of the buildings have been, besides the general ones previously mentioned, the following ones: the total absence of seismic design for lateral loads, too small cross-sections of the reinforced concrete columns, the transformations undertaken during their service life, especially at the first floor, that led to a decrease of stiffness and resistance primarily to lateral loads, low quality of building materials – especially of concrete. Besides the cases of collapse, very many cases of heavy damage of structures have been observed at old, tall, blocks of flats. The columns of the lower three stories have been mainly affected, as a rule, by damage like: wide cracks up to concrete expulsion, reinforcement bar buckling, and total collapse of the concrete section. This damage has been observed especially at the ends of corner, or marginal columns. The failure occurred under combined action of eccentric compression and shear.

Three cases of collapse of new apartment buildings have been recorded: two tall buildings in Bucharest where the groups of apartments located around one extreme staircase collapsed (Lizeanu and OD16), and a four-story building in Valea Calugareasca, near to the Ploiesti town, where the first open story used for shopping areas collapsed. The third collapse of a modern building occurred in a 1-year old, 10 story building. There, a 40 m middle unit of a six-unit block, collapsed between the expansion joints. The building had precast slabs with cast-in-place transverse and longitudinal walls. The adjacent unit to the west in the same block revealed local failure of the transverse (shear) wall in the first floor, exposing a concrete of apparently inferior quality. The 15 cm thick walls had light vertical and horizontal reinforcement. All other identical units of the several neighboring blocks showed no apparent distress. *A lot of photos of damaged and collapsed buildings during the Vrancea March 4, 1977 earthquake can be found in the EERC Steinbrugge collection*. On the outskirts of the city unreinforced masonry walls in many older one-and two-story dwellings were extensively damaged (Figure 4,b).

(a) (b)

Figure 4 (a). Typical one story adobe/wood wall dwelling in Vrancioaia. (b). Typical old two-story unreinforced masonry wall dwelling, Bucharest, 1977 (Rojahn,1977).

Of the major type of modern constructions in existence at the time of the March 4, 1977 earthquake, the stiffer buildings sustained less structural and non-structural damage than the more flexible ones. Their good performance may be related to the fact that their fundamental or lowest natural frequencies of vibration have been observed to be high (2 to 5 Hz) in comparison to the predominant frequencies of high-amplitude ground motion in Bucharest (Rojahn, 1977).

The national strategy for retrofitting the buildings damaged by the 1977 earthquake was established by the Romanian Government of that period, and the following strategy was enforced:

- *for old buildings (built before 1940) – the same resistance they had before the 1940 earthquake;*
- *for new buildings (built after 1945 and before 1977) – the same resistance they had when they were designed;*
- *retrofitting of the buildings damaged by the 1977 earthquake will consist of strict local repairing of damaged elements; additional measures for seismic protection are not allowed.*

The adopted strategy was an enormous mistake. Many of the buildings designed prior to 1977, without seismic rules, or according to past standards, have inadequate lateral strength and poor energy dissipation capacity for withstanding a major earthquake. The non-ductile type reinforced concrete frames, a characteristic of the buildings constructed in Bucharest before 1977, have been identified as one of the greatest hazard to society. Today, taking into account the expected incidence of another strong earthquake, the community of structural engineers is trying to diminish, as far as this is possible, the seismic vulnerability of more than 7000 buildings known to have accumulated a significant amount of cumulative structural damage.

7. SHORT ON SEISMIC LEGISLATION

The year of birth of the Romanian earthquake engineering is considered the year of 1940. Following the 1940 seismic event, preliminary instructions regarding the earthquake resistant design of the reinforced concrete and masonry buildings were published by the Ministry of Public Works and Communication (1941). After the Second World War, the same institution developed new technical guidelines titled “Instructions for preventing the damage of buildings located in seismic zones” (1945). Later, in 1963, the first Romanian seismic code was published. This code underwent successive modifications in 1970, 1978, 1981, 1990, 1992 and 2006.

8. BEHAVIOR OF DWELLINGS DURING THE 1986 AND 1990 EARTHQUAKES

In what concerns the behavior of the dwellings during these seismic events, the first fact to be mentioned is that no full structural collapse was recorded. Structural damage was observed in most cases in old buildings not designed to resist earthquakes, in locations where instrumental intensities were VII or more. The towns most affected were towns where high intensities met a more important older building stock (Sandi, 1986). The earthquakes of 30-31 May 1990 were quite strong, but did not cause severe damage to any residential buildings.

9. SOME FINAL REMARKS

- No code was enforced before the November 10, 1940, earthquake. The buildings constructed up to 1940 were designed only for gravity loads, without direct concern for earthquake resistance. As a result, these buildings had random aseismic safety. Due to the lack of any consistent philosophy in their structural setting and proportioning to resist seismic forces, 28 of them collapsed during the 1977 earthquake. All the remaining constructions belonging to this category make up the most vulnerable building stock to future strong seismic actions.
- The greater effect of the 1977 earthquake in Bucharest was on flexible, 6...12 story high reinforced concrete structures of low ductility, without shear walls. These buildings have a fundamental period of vibration of the order of 0.6÷1.4 s, which place them on the ascending branch of the 1977-resulted spectrum. Progressive damage during the event should have caused a lengthening of their period and an increase in the lateral forces acting on them. In contrast, rigid structures of large panel or frame construction with shear walls, of the same height, as well as 1÷3 story masonry dwellings sustained little damage. These buildings have much shorter periods of the order 0.2÷0.5 s and they belong to the early, more subdued part of the 1977 spectrum.
- The period 1992–2007 was influenced by some important external factors: the radical political change of late 1989 and the prospects of implementation of EUROCODES in engineering activities. The political freedom reached and the free market conditions introduced had some negative side effects, in the sense that the control of design and construction activities decreased, leading to some cases of chaotic phenomena. There were also cases of wrong interventions on existing structures (e.g. demolition of some partitions, or even of some structural members, in buildings). The application in practice of regulations was affected in some cases by a kind of randomness. The design and construction engineers had to comply in several cases with requirements of the clients, who often knew too little about earthquake protection and/or had no interest in spending for earthquake protection. This led to situations in which, in spite of very limited, random, information at hand, one can state that there are not few cases of increased seismic vulnerability of buildings.

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