Performance of RC Cast-in-Place Buildings During The November 26, 2019 Albania Earthquake

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Research Article

Keywords: reinforced concrete, infill masonry, 2019 November Albania earthquake, damage, non-structural elements, seismic performance

Posted Date: November 2nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1027850/v1

Abstract

This paper documents performance of cast-in-place reinforced concrete (RC) buildings in the Durrës during Albania earthquake of 26th of November 2019 (M_W 6.4). Both mid- and high-rise RC buildings were affected by the earthquake, experiencing structural and/or non-structural damage and even collapse in some cases. The authors performed a reconnaissance study after the earthquake and were involved in seismic assessment of buildings in the affected area. Besides the observations related to physical damage related to RC buildings, the paper also presents results of a statistical analysis of damaged RC buildings in the Durrës city. The discussion in the paper is focused on damage patterns and failure mechanisms that are relevant for the seismic response of RC structures. Most common damage pattern is related to masonry infill walls, which experienced damage and failure in some cases, and affected the performance of adjacent RC columns due to the infill/frame interaction. Taller RC framed buildings (10 storeys and higher) were expected to have RC shear walls; however, these walls were reportedly absent in the damaged buildings of this type. In some cases, masonry infill walls (instead of RC shear walls) were used in the elevator shaft areas, which resulted in inadequate seismic performance. Two case study buildings were presented in detail to illustrate seismic behaviour of cast-in-place RC buildings. The case study is based on field observations after the earthquake and a detailed seismic assessment study. Finally, relevant lessons and recommendations are presented in light of the observed performance of RC buildings.

1. Introduction

A M_W 6.4 earthquake occurred in the western region of Albania on 26 November 2019, causing 51 casualties, more than 913 injuries and widespread damage to buildings and infrastructure (Government of Albania 2020). The epicentre was located approximately 16 km north of Durrës (population approximately 290,000), the second largest city in Albania, which was most severely affected by the earthquake (IGEWE 2019). The capital city, Tirana (population approximately 910,000), as well as surrounding urban areas, were also significantly affected. Papadopoulos et al. (2020) reported that the damage was most pronounced in two elliptical regions with major axes aligned in the NW-SW direction. Total losses due to the earthquake were estimated to more than 985 million Euros. Housing sector suffered most significant damage. It was estimated that 18% of all housing units in the affected area required either reconstruction or rehabilitation (Government of Albania 2020). Damages in other sectors, including educational facilities and hospitals, were also reported in the affected municipalities (Government of Albania 2020).

The November 2019 earthquake was the most severe seismic event in the country since 1979 and the first major earthquake that exposed Albanian building stock after the Albanian seismic design code KTP-N2.89 (1989) was last revised in 1989. The earthquake affected an area that experienced rapid development after the fall of communist rule in early 1990s and subsequent major political and economic changes in the country. At the same time, significant changes occurred in construction sector, both in terms of construction technology and building typologies. In many cases, construction boom was also accompanied by spread of informal construction practices (Government of Albania 2020; Chryssy and Augustinius 2010; Tsenkova 2012).

Before 1990, masonry was the predominant construction technology in Albania, as reflected in the design codes, since design provisions were more focused on masonry than reinforced concrete (RC) structures, as observed after the 1988 Tirana earthquake (M 5.7) (Carydis et al. 1988). During the same period, RC construction was practiced in Albania at a limited scale, and designs of construction features of RC buildings were different from buildings of more recent vintages. Since the 1990s, RC has been predominant construction technology in Albania. The latest national seismic design code KTP-N2.89 (1989), published in 1989, included comprehensive set of design and detailing provisions related to RC buildings, however it did not reflect more recent seismic design practices that were introduced based on the experience from neighbouring countries. Furthermore, advances in RC construction technology were unfortunately not accompanied by adequate construction quality assurance by the responsible government agencies.

Damage of masonry infills in RC framed structures was widespread in the area affected by the November 2019 earthquake; this is reportedly one of the most common damage patterns in RC framed structures exposed to moderate earthquakes (Braga et al. 2011; Barbosa et al. 2017; Masi et al. 2019; Perrone et al. 2019). Structural damage and collapse of RC buildings were also reported, particularly in coastal areas. Papadopoulos et al. (2020) reported that clusters of buildings located in weak soil areas suffered more extensive damage, indicating that soil conditions played an important role in the earthquake. Preliminary reconnaissance data released shortly after the earthquake (Alam et al. 2019) and subsequent surveys by several research groups, including the authors of this paper, suggest that damage to RC buildings was more pronounced in the Durrës area, whereas masonry buildings in other cities experienced more damage.

This paper presents findings of a reconnaissance study performed by the authors in December 2019, which was a joint effort of four members of the Serbian Association for Earthquake Engineering (SUZI-SAEE) and two Albanian earthquake engineers. The team visited Durrës, Tirana, and smaller towns and villages, including Thumanë, Bubq, Krujë and Fushë-Krujë. A detailed overview of the reconnaissance study is presented elsewhere (Nikolić-Brzev et al. 2020). Due to the specific circumstances related to evolution of RC building construction practice in Albania, the November 2019 earthquake was a source of valuable information related to the seismic behaviour of RC buildings, ranging from non-engineered or inadequately engineered buildings to modern buildings designed according to the Eurocodes (Government of Albania 2020; Alam et al. 2019). This paper presents the main observations related to the seismic performance of RC buildings in Albania in the 26 November 2019 earthquake and discusses the causes of the observed damage. The information contained in the paper is expected to be of interest to earthquake engineering community since it fills a gap in the knowledge related to recent earthquakes in the Balkans.

2. Seismological Aspects

Albania is located in an area characterized by high seismicity in which strong earthquakes have occurred periodically throughout history (Papadopoulos et al. 2020; Aliaj et al. 2010). Based on the current seismic hazard zonation map of Albania and micro-zonation maps for Durrës and Tirana, it can be expected that Durrës can experience an earthquake of maximum intensity IX per the MSK-64 scale, while the maximum intensity VIII can be expected in certain areas of Tirana. Recent probabilistic seismic hazard assessment (PSHA) studies have estimated the Peak Ground Acceleration (PGA) of 0.25g or higher for a 475-year return period earthquake at rock site in Durrës and Tirana (Aliaj et al. 2010; BSHAP 2020; Aliaj et al. 2004).

The 26 November 2019 earthquake was preceded by a M_W 5.6 earthquake with approximately same epicentre which occurred on 21 September 2019. The September 2019 earthquake caused a considerable damage, mainly non-structural, and affected roughly the same area as the November 2019 earthquake (Papadopoulos et al. 2020; Bossu et al. 2020). The last 24 hours before the November 2019 earthquake were characterized by an increased seismic activity with foreshocks of magnitude up to 4.0. A strong aftershock activity throughout the day of the main shock, with three aftershocks with magnitude M_W 5.1 to 5.4 (Freddi et al. 2021), led to increased panic and caused further building damage (Alam et al. 2019). Aftershocks with magnitude up to about M_W 4 occurred during several months after the main shock (Freddi et al. 2021).

The 26 November 2019 earthquake, its foreshocks and aftershocks, were recorded by seven stations of the Albanian Strong Motion Network, and the data is publicly accessible online through the IGEWE website (IGEWE 2019). Unfortunately, the Durrës station (closest to the epicentre), recorded only the first 15 seconds of the main shock due to a technical issue (Duni and Theodoulidis 2019). The stations which recorded the highest accelerations were located in Durrës and Tirana, and the 5% damped elastic spectra of the September and November 2019 earthquakes are presented in Fig. 1. The recorded PGA values were 0.12g and 0.19g in the Durrës station for the September and November 2019 earthquakes, respectively, while the corresponding maximum recorded PGA values in the Tirana station were 0.18g and 0.12g. It is interesting to observe that the Tirana station recorded higher accelerations during the September 2019 earthquake, while the Durrës station site recorded higher accelerations during the November 2019 earthquake.

Even though the response spectra based on the acceleration records from the Durrës station were developed using a partial record of overall ground shaking, it can be seen from Fig. 1 that the November 2019 earthquake induced high seismic demands in taller (mid- and high-rise) buildings, characterized by fundamental vibration periods of 0.5 sec and higher. On the other hand, September 2019 earthquake, as recorded in the Durrës station, was characterized by smaller spectral accelerations within the same period range (0.5 sec and higher). It is interesting that these earthquake spectra were comparable in other period ranges, e.g., lower periods characteristic for rigid low-rise structures.

It is also noteworthy that significantly larger spectral accelerations were reported at the Durrës station (particularly N-S component with the maximum spectral acceleration on the order of 0.6g) compared to other stations (see Fig. 1a,b). However, it should be noted that the Durrës station is located in weak soil conditions (Freddi et al. 2021), characterized by shear wave velocity $v_{s,30}$ = 202 m/s, while the Tirana station is located in better soil characterized by $v_{s,30}$ = 312 m/s (IGEWE 2021), hence it is difficult to perform direct comparison of these spectra. Vertical acceleration spectra for the Durrës station (Fig. 1c) also show relatively high vertical accelerations, which can be attributed to the proximity of epicentre.

Figure 1 Elastic response spectra of the ground motion records for September and November 2019 earthquakes (5% modal damping ratio): horizontal components (E-W and N-S) a) Tirana, b) Durrës and c) vertical component

3. Design Codes And Construction Practice Related To Rc Buildings

3.1 Design codes in Albania

Historic development and the extent of enforcement of Albanian building codes in practice and the construction typologies addressed by these codes are strongly related to political and economic setting in the country during different time periods. A timeline of Albanian design codes, major earthquakes, and construction typologies characteristic for different time periods is presented in Fig. 2.

The first seismic provisions were published in 1952 (Council of Ministers 1952), and they were incrementally improved in the 1963 seismic design code (Ministry of construction 1963), which included provisions for buildings and other types of structures (Baballëku and Myftaraga 2020). According to the code seismic action was considered by taking into account dynamic properties of the structures and elastic response spectra. The first design code for RC structures in Albania was issued in 1960 (KTP-NB 60 1960). Subsequent revisions of the Albanian design codes (KTP) and construction codes (KTZ) were issued in 1978 and 1979, but the updated versions did not bring significant improvements in the seismic safety compared with the 1963 seismic code. The 1978 seismic design code (KTP-N.2-78 1978) was mostly focused on masonry structures and general aspects, such as the seismic action, structural regularity, seismic gaps and other general rules. Although masonry was the predominant construction technology before 1989, RC technology was also used for construction of important public facilities such as hospitals and university buildings. Seismic design of RC structures according to the code was largely based on force-based design approach and detailing of RC structures was not adequately addressed by the code, hence the seismic safety of these buildings was at risk due to a lack of proper detailing for ductility and large inelastic demands. The code was amended in 1982, based on the lessons learned from the 1979 Montenegro earthquake (Stermasi et al. 1980).

The 1989 seismic design code KTP-N.2-89 (1989) brought significant advancements compared to previous code editions and was in line with other international seismic design codes at the time. The code included reinforcement detailing rules for critical regions of RC members, design provisions for masonry infills in RC framed structures, and advanced methods of seismic analysis. Reinforcement detailing requirements for RC frames illustrated in Fig. 3 were prescribed depending on the seismic intensity at the construction site, with more stringent requirements for sites located at higher seismic intensities. For example, maximum spacing of longitudinal bars enclosed by hoops was limited to 30 cm for seismic intensity up to VIII and 20 cm for intensity above VIII per MSK-1964 scale. Critical regions in which denser transversal reinforcement was required were prescribed for both beams and columns (see Fig. 3 for intensity above VIII). The length of the critical region was required to be twice the depth of the beam for beams (for all seismic intensities), whereas for columns the length depended on the clear height, the size of the column and the seismic intensity (for intensity above VIII, see Fig. 3).

Several limitations of the code have become apparent over time, including the lack of explicit treatment of damage limitation, serviceability criteria, and incomplete provisions for ductile detailing of RC members. It is important to mention that KTP-N.2-89 (1989) was the official seismic design code in Albania at the time of the November 26, 2019 earthquake.

The fall of communism in Albania occurred in 1990, shortly after the 1989 seismic design code was released. This period was also characterized by a shift towards RC as the preferred construction technology and a rapid urbanisation of Tirana and Durrës, largest cities in the country. Unfortunately, a significant increase in informal construction practices also took place during the same period (Chryssy and Augustinius 2010).

After 1990 structural engineers in Albania started to apply codes from neighbouring countries and, more recently, the Eurocodes, however the application of international codes was done on a voluntary basis - either proposed by design engineers or requested by investors of important projects. As of this writing the Eurocodes have the status of National Standards, but their implementation is still optional.

3.2 Construction practices

This section presents an overview of RC construction technology in Albania, with the focus on cast-in-place RC technology, which has been discussed in four distinct time periods: i) before 1960, ii) from 1960-1990, iii) from 1990-2000, and iv) 2000-present.

Prior to 1960s masonry was the prevalent construction technology in Albania, and its applications ranged from low-rise dwellings to major heritage structures, such as fortresses. It was a common practice to use different masonry elements (units) in a building, for example to construct stone masonry walls at the ground floor level and other materials (adobe, clay bricks, timber) at the upper floor. During that period majority of Albanian population occupied rural areas of the country. RC construction technology in Albania started after 1920, mostly through involvement of Italian companies, and was limited to bridges and public facilities. The first cement manufacturing plant in the country, with 12,000 tons annual capacity, was constructed in Shkodra in 1927.

Due to increased housing demand after World War II, large-scale construction of multi-family (apartment) buildings started in urban areas of Albania. These buildings were mostly constructed using unreinforced masonry (URM) technology. In the period from 1945-1960 some public facilities (hospitals, schools, etc.) were constructed using a mixed structural system, consisting of exterior loadbearing URM walls and interior RC columns, which were mostly intended to sustain the effect of gravity loading.

The period from 1960-1990 was characterized by wider use of RC construction technology, mostly for public facilities (schools, hospitals, etc.) and multi-family residential buildings (usually 5-6 storeys high). Majority of residential RC buildings were constructed using prefabricated construction technology (Guri et al. 2021), while cast-in-place RC technology was more often used for construction of public facilities which were characterized by larger open spaces. During that period standardized designs were prepared by a few specialized government design institutes, while local design offices were responsible for developing designs for building interventions, which were mostly related to foundations and depended on local site conditions.

Limited use of cast-in place RC frame system has been influenced by several factors, including limited capability to produce good quality in-situ concrete, hence concrete need to be transported from a plant to the construction site. Also, steel reinforcement was partially locally available and considerable amount had to be imported at a higher cost. RC buildings constructed during that period were regular in plan and elevation. Building blocks were separated by means of construction joints, but the size of such joints was determined without seismic considerations. Although the codes as early as in 1978 required the consideration of plastic behavior of RC frames under seismic loading through the development of plastic hinges, they did not contain sufficient provisions to ensure an adequate fulfilment of this requirement. Reinforcement detailing provisions for RC columns and beams were limited, but included a provision for closer tie spacing in columns within the spliced region of longitudinal reinforcement. Prefabricated concrete hollow core slabs were commonly used for construction of suspended floor slabs, and RC columns were supported by pad footings connected by RC tie-beams. In the 1980s some RC buildings, particularly public facilities, were constructed using a dual system, consisting of RC frames and masonry shear walls in elevator cores and exterior walls, although seismic design of dual systems was not covered by the codes. Masonry units used for construction of infill and partition walls were solid clay bricks, but in 1980s silicate bricks emerged as a common type of masonry units and perforated bricks started to be used for infill walls. Some RC buildings of the 1980s vintage were constructed using a hybrid structural system, with RC frames at the ground floor level which was used for service purposes, while upper floors were constructed using URM walls which were in some cases confined with vertical and RC horizontal elements like a confined masonry system. This hybrid system was characterized by a soft storey irregularity, and these buildings experienced extensive damage or even collapse in the 2019 earthquakes, as discussed later in the paper. In general, quality of construction materials (concrete and masonry) appears to have deteriorated over time, particularly in the 1980s.

Major political changes that took place in Albania in the 1990s also affected the construction sector. Rapid and uncontrolled construction activities, particularly in urban and suburban areas, resulted in substandard construction quality and many buildings were not designed or constructed in compliance with the KTP-N.2-89 code (1989). These buildings were characterized by design flaws (e.g., soft storey irregularity) and substandard quality of building materials, particularly concrete. After the construction was completed, in some cases inappropriate interventions were made, such as perforations in existing walls and vertical extensions. By and large, these buildings showed poor performance in the November 2019 earthquake - an example is “Këneta”, a marsh area populated by RC buildings of the 1990s vintage near Durrës.

In the early 2000s construction of high-rise RC buildings became more prominent in urban areas. These buildings were characterized by services at the lower 1 or 2 floors and residential area at the upper floors. This period was characterized by a continuous improvement in the field of construction (both design and execution). The adoption of European standards (Eurocodes) and their implementation on some projects has had a positive influence on the quality of design and construction materials. The most common structural systems were RC frames with masonry infills and a dual RC system, which consists of frames and shear walls. However, even in these modern buildings, implementation of seismic design criteria is not adequate in some cases, mostly due to a lack of control within the construction industry and a lack of necessary reviews pertaining to structural design. Common deficiencies observed in these buildings include structural irregularities (both in plan and elevation); frequent use of shallow floor beams in RC frame systems without an adequate accompanying lateral load resisting system, and “heavy” masonry infill walls at upper floors.

4. Statistical Analysis Of Post-earthquake Rc Building Damage Surveys

This section presents available data related to the damage of RC structures in the Durrës municipality due to the November 2019 earthquake. Firstly, the census data were used to estimate the exposure of RC buildings in the Durres municipality – note that both the 2001 (INSTAT 2001) and 2011 (INSTAT 2013) Census were referenced for this purpose. Subsequently, the official post-earthquake damage survey data collected after the November 2019 earthquake, was used as a basis for the damage statistics related to RC buildings. The review of the census data revealed that the information which was collected as a part of the census surveys was not readily suitable for the post-earthquake damage analysis, hence a few assumptions had to be made while performing analyses presented in this section.

4.1 Analysis of the Census data

Albanian Census provides building information at four different administrative levels: country, region (i.e., prefecture), municipality, and administrative unit (i.e., commune). Based on the available data and the extent of damage to RC buildings, the authors decided to analyze data from the Durrës municipality, which consist of six administrative units: Durrës, Ishëm, Katund i Ri, Manëz, Sukth, and Rrashbull. The 2001 Census contained the information regarding the main structural system and material for the national building stock, however it is expected that such data is unreliable (low quality). Furthermore, this type of data was presented only on the country level, not on the municipality level. Unfortunately, the 2011 Census did not include any information related to the structural system or material for the surveyed buildings, but it contains information regarding the year of construction (construction date). In addition, the 2011 Census classified the buildings according to their height (number of storeys) into the following categories: 1 storey, 2 storeys, 3-5 storeys, and more than 5 storeys.

This study is limited to mid- and high-rise buildings (building height of 3 or more storeys) in the Durrës municipality, because these buildings were likely constructed using RC technology – this is one of the assumptions of the study. The authors believe that structural system for a building can be determined with a reasonable accuracy, provided that the year of construction and the number of storeys are known. For statistical analysis purposes the buildings were classified into buildings with 3-5 storeys and buildings with more than 5 storeys.

Furthermore, since the year of construction for different building height categories was available only for the Durrës region, but not specifically for the Durrës municipality, it was assumed that the building age distribution (year of construction) for the Durrës municipality is same as for the Durrës region (which was available from the 2011 Census). This is another key assumption of the study.

Finally, it was assumed that the RC construction practice started in Albania in 1960s, hence the buildings constructed before 1960 were not considered in the study. In addition, it is expected that a large number of RC buildings were built in the period between 2001 and 2011, therefore the authors mostly relied on the 2011 Census data in this study.

The authors assumed that the buildings taller than 5 storeys were constructed using RC technology. Also, it was reasonable to assume that the buildings constructed after 1991 were cast-in-place RC structures, while prefabricated RC technology was practiced during the period 1960-1990. These assumptions were based on the authors' knowledge regarding the construction practices in Albania as well as data from (UNDP and MLGD 2003). Furthermore, 3 to 5 storey high buildings which were constructed after 2000 were classified as cast-in-place RC structures, based on the construction practice in Albania at the time. For the period from 1960 to 2000, the authors assumed that approximately 60% of 3- to 5-storey buildings were RC structures, while the remaining 40% are masonry structures. It should also be noted that most RC buildings built before 1991 are 5- or 6-storey high. Furthermore, it was also assumed that RC buildings constructed in the period 1960-1990 were mostly prefabricated large panel prefabricated buildings, while the buildings constructed from 1991-2001 were mostly cast-in-place RC structures.

Census data also contains buildings without any information. While it might be reasonable to assume that these buildings were constructed after 1990, where informality in construction was high, these are excluded from the analysis presented in this paper due to uncertainties in terms of their height and structural system.

Another limitation of the Census data was the lack of information regarding the buildings constructed in the period from 2011 to 2019. It is expected that a considerable number of RC structures were constructed during that period. Based on the INSTAT data (INSTAT 2021), it can be estimated that the number of RC buildings constructed from 2011-2019 amounted to approximately 35% of the total number of RC buildings constructed in the period from 2001-2011. This assumption was used to estimate the number of RC buildings in the period from 2011-2019. Given all the limitations and assumptions, an approximate estimation related to the distribution of RC buildings based on the height (number of storeys) and year of construction for the Durrës municipality was made by the authors (see Fig. 4). Total number of RC buildings with 3 or more storeys in the Durrës municipality is estimated at 2593 buildings, out of which 1728 buildings (i.e., 67% of the total number of considered buildings) are 3 to 5 storeys high, while 865 buildings (i.e., the remaining 33%) have more than 5 storeys. Furthermore, it can be observed that only 22% of RC buildings with 3 to 5 storeys were built before 1990 and that the majority of these buildings (i.e., 56%) were built after 2001. Similarly, 74% of buildings with more than 5 storeys were built after 2001, while only 90 (i.e., 10%) were built before 1991.

4.2 Damage data

The authors had access to three damage datasets for the Durrës municipality: i) a dataset which contained information regarding the number of buildings in each damage state (DS), but without information regarding the number of storeys or the structural system, ii) a dataset which classified the damaged buildings into two categories based on the number of storeys (3-5 storeys and 6 or more storeys – same as the 2011 Census data) and iii) information from literature related to damage data (Verzivolli et al. 2020). The damage categorization considered in the second dataset included 3 classes: i) undamaged (DS0), ii) slight to moderate damage (DS1,2,3) and iii) severe damage/collapse (DS4,5). A brief overview of damage states used to categorize building damage after the 26 November 2019 earthquake is presented in Table 1.

Table 1
Description of damage states used to categorize building damage after the 29 November 2019 Durrës earthquake (Stavros et al. 2019).

Damage State	Structural Damage	Non-Structural Damage	Description
DS1	None	Slight	Minor plaster cracking on the walls. Cracking of partition walls.
DS2	Slight	Moderate	Cracking in the tie and lintel beams. Cracks in the partition walls. Plaster coating cracking and falling off the walls. Mortar falling from the connections of wall panels.
DS3	Moderate	Severe	Cracks in columns or column-beam connections or wall joints. Concrete spalling. Reinforcement visible. Large cracks in the partition walls.
DS4	Severe	Very Severe	Large cracks in structural elements. Columns tilting. Severe damage to several columns.
DS5	Very Severe/ Collapse	Very Severe/ Collapse	Partial or total collapse of the building.

Since the statistical analysis considered only buildings with 3 or more storeys, the second damage dataset that contained the information on building height was used to estimate damage distribution among RC buildings in the Durrës municipality (Fig. 5). Neither dataset provided information regarding the structural system of damaged buildings. However, following the assumptions stated earlier in this section, buildings with 6 or more storeys were considered as RC buildings.

Buildings with 3-5 storeys that suffered severe damage or collapse (DS4,5) could also be classified as RC buildings, based on the observations from the authors' reconnaissance visit to the Durrës municipality (Nikolić-Brzev et al. 2020; EERI 2021). Furthermore, it was estimated that 75% of 3-5 storey buildings that suffered slight to moderate damage could be classified as RC buildings. The estimate was based on the location of the considered damaged buildings, which were mostly located in the areas urbanized in the 1990's when RC became the prevalent construction technology. Finally, number of undamaged buildings (DS0) was obtained by subtracting the number of buildings in other damage classes from the total number of buildings in the Durrës municipality (see Fig. 4).

Figure 5 presents the estimated number of RC buildings categorized in different damage states following the 26 November 2019 earthquake. Out of 1,728 buildings with 3-5 storeys in Durrës municipality, 120 buildings (i.e. 7%) suffered severe damage or collapse (DS4/5), 720 buildings (i.e., 42%) experienced minor to moderate damage (DS1,2,3), while the remaining 888 buildings (i.e., 51%) remained undamaged. The results showed that taller buildings (6 storeys and higher) experienced less damage than 3-5 storey buildings. However, during field observations it was observed that the taller RC buildings (with 6 storeys or more) experienced significant non-structural damage. According to the results of the presented analysis for the buildings with 6 or more storeys, 26 buildings (i.e., 3%) were severely damaged or collapsed (DS4/5), 274 buildings (i.e., 32%) suffered minor to moderate damage (DS1/2/3), while the remaining 564 buildings (i.e. 65%) remained undamaged (DS0).

5. Structural Damage Of Cast-in-place Rc Buildings In The 2019 Albania Earthquakes

5.1 Overview

Field surveys of buildings damaged in the November 2019 earthquake indicated that majority of buildings that collapsed or suffered significant damage had a cast-in-place RC moment frame system with masonry infills (Freddi et al. 2021; EERI 2021). This section presents observations regarding the structural damage patterns and causes of damage and collapse of RC buildings based on a field reconnaissance study performed by the authors.

Typical structural deficiencies observed in RC frame buildings affected by the 2019 earthquakes include: i) flexibility of RC frame structures causing masonry infill damage, ii) “soft storey” irregularity, iii) damage of RC columns, iv) plan irregularity causing torsional effects, v) inadequate reinforcement detailing, and vi) inadequate size of seismic gaps, which caused pounding of adjacent buildings.

Despite several structural deficiencies observed during the survey, many RC frame buildings in Durrës which suffered severe damage during the November 2019 earthquake remained undamaged in the September 2019 earthquake, which was characterized by a lower shaking intensity (Lekkas et al. 2019). The authors believe that the underlying cause of severe damage for RC frame buildings in the November 2019 earthquake was a high seismic demand, reflected by high spectral accelerations within the period range characteristic for flexible RC frame structures. When exposed to high seismic demand, various design and construction deficiencies in these buildings were revealed. It is believed that structural irregularities significantly affected seismic performance of these buildings. Studies (Freddi et al. 2021; EERI 2021) on ground motions recorded during the earthquake showed that spectral accelerations during the November 2019 earthquake were approximately equal to elastic spectral accelerations according to the KTP-N.2-89 code (1989). The fundamental periods for low- and mid-rise RC buildings in Durrës were in the range from 0.5-1.0 sec, with the PGA of 0.19g and the corresponding maximum spectral acceleration above 0.5g (Fig. 1). The November 2019 earthquake can be considered as design level earthquake for the affected sites, except for flexible structures where seismic demand was higher than expected for a design level earthquake. It is important to point out that majority of RC frame buildings exposed to the earthquake performed in line with the basic Life Safety seismic performance requirement set by the design codes, according to which significant structural damage is acceptable but overall building collapse must be avoided.

5.2 Excessive flexibility of RC frame structures

RC frame structures with masonry infills became dominant structural system in construction practice in Albania after the adoption of Albanian seismic code KTP-N.2-89 (1989). In most cases, floor systems are one-way or two-way ribbed RC slabs infilled with polystyrene (Fig. 25a and Fig. 30a), which was provided to reduce the floor self-weight. Interior floor beams are wide and shallow, whereas deeper beams are placed at the perimeter of the slab (edge beams). Note that KTP-N.2-89 (1989) prescribed the minimum depth of 30 cm for

RC beams, hence the beam depth was in line with the minimum code requirements. Since these buildings were usually designed and constructed either without RC shear walls or with a relatively small number of walls, the main lateral load resisting system is in the form of relatively flexible RC moment frames.

Due to high flexibility of RC frame building structures in Albania, masonry infills had a significant influence on their behaviour in the November 2019 earthquake. Layout of masonry infills varied in plan and elevation of a building, depending on the building function and its position relative to adjacent buildings. In many cases, buildings had open ground and first floors; hence the infills were constructed only at upper floors. In other cases, masonry infills were unevenly distributed in plan – this was usually the case with "corner buildings" (located at corners of building blocks). It should be noted that the effect of masonry infills on the behaviour of these buildings depended on the relative stiffness ratio of RC frame elements relative to masonry infills, hence different damage patterns were observed in the buildings characterized by different heights. In most low- and mid-rise RC buildings, masonry infills significantly contributed to the extent of damage or collapse. Most buildings that sustained significant damage or collapse during the November 2019 earthquake were constructed from 1990 to 2010. Although taller RC frame buildings from that period experienced large interstorey drifts and significant damage of masonry infills, RC structural elements did not experience notable damage due to higher strength and stiffness of RC frames.

5.3 Damage and collapse of RC buildings due to "soft storey" effect

"Soft storey" collapse mechanism was observed in several buildings within the epicentral area, particularly in the Durrës area, as reported in reconnaissance studies (Freddi et al. 2021; EERI 2021). This mechanism was caused by an irregularity in elevation, where stiffness of one floor is significantly less than adjacent floors. Buildings characterized by this irregularity had unevenly distributed masonry infills in these buildings. The buildings had an open space at the ground floor level, which was used for various purposes (e.g., as a garage, office space, shops, restaurants, etc.), while masonry infills were constructed at upper floors, which were typically used for residential purposes (as apartments). Due to the presence of masonry infills at upper floors and the resulting increase in stiffness, deformation demands on RC columns at open lower floors were significant. Significant damage and collapse of several RC buildings located in the epicentral area of the November 2019 earthquake can be attributed to this failure mechanism. For example, Hotel Ljubljana, located in the severely affected area of Durrës (Fig. 6), experienced this type of collapse. Note that the hotel also had a vertical extension (three floors were added after the original construction was completed), which could have also contributed to collapse

5.4 Damage patterns observed in RC columns

It was observed that some columns in RC buildings experienced damage due to frame-infill interaction and due to "short column" effects. In some cases, cracks in RC columns with rather small cross-sectional dimensions appeared due to interaction with masonry infill walls, characterized by significantly higher stiffness than the adjacent frame elements. Fig. 8 shows damaged RC columns in a building located in Durrës. It was observed that these columns have 6 mm ties with 90° hooks were observed, at 10-13 cm spacing (Fig. 8a). It can be noticed that cracks propagated from infill walls into adjacent RC columns.

The “short-column” effect was observed in buildings with masonry infills placed up to a limited height due to presence of openings, e.g., windows, that is, partial infills (Fig. 9a). The resulting concentrated infill stiffness reduces the effective column height and increases shear forces which act on the part of a column which is not in direct contact with the infill. Failure of short columns may occur at sufficiently high seismic demands. The “short column” effect may also occur when a part of the staircase (usually intermediate landing) is supported by the RC columns (Fig. 9b).

5.5 Damage due to plan (torsional) irregularity

One of the most common types of irregularity observed in the affected RC buildings was a plan irregularity which is due to asymmetrical stiffness distribution in plan, and caused significant torsional effects. Plan irregularity in RC buildings affected by the 2019 Albania earthquakes was caused by asymmetrical distribution of masonry infills and stairs, and caused significant damage and even collapse due to torsional effects. Fig. 10 shows a 7-storey RC frame building located at the seaside area of Durrës. According to Google Earth images, the building was built between 2000 and 2005. The last floor was under restoration and had a setback located on N-W side of the building. Floors and roof were supported by a grid of 4×6 rectangular columns arranged in a regular pattern, with spans ranging from 3.5 - 4.2 m (Fig. 10c). Columns were approximately 30 cm wide and 50 cm deep. It was noticed that most columns in longitudinal perimeter frames were aligned such that their depth was perpendicular to the frame direction, which reduced torsional stiffness of the building. The floor system was in the form of a two-way ribbed RC slab with polystyrene filling and shallow RC beams (explained earlier in this section). The beams were approximately 70 cm wide and 30 cm deep. The perimeter frame at S-E façade had 30×50 cm beam at the first floor level, but the authors were not able to confirm whether similar beams were present at upper storeys.

The stairs were located at the north corner of the building and were supported by the beams and adjacent perimeter columns (see Fig. 10c). The building had an open ground floor and large openings in the exterior infill walls at the N-E and N-W façade, near the stairs (see Fig. 10a and Fig. 10b). It is believed that both stairs and infills, concentrated at the north corner of the building, had adverse local and global effects on the seismic performance of the flexible RC frame structure. Fig. 10d) shows damage of masonry infills on the north side, whereas Fig. 9b) shows shear and axial load damage of a “captive” RC column supporting the stairs. Globally, stairs and adjacent infill walls caused higher displacement demands on perimeter frames due to torsional effects. As a result, perimeter columns at the S-E façade experienced shear and flexural damage and had to be propped, as shown in Fig. 10b).

5.6 Inadequate reinforcement detailing of RC frame elements

Several reinforcement detailing flaws were observed in majority of damaged and collapsed buildings surveyed during the reconnaissance study. Examples of these flaws are shown in Fig. 11 and summarized next (Milićević et al. 2021):

(a) Only perimeter tie provided in RC columns within “critical” regions;
(b) Widely spaced stirrups/ties in “critical” regions and/or outside “critical” regions of beams and columns;
(c) Lack of stirrups or complete absence of stirrups in beam-column joints;
(d) Small tie size (6 mm diameter) in RC columns;
(e) Ties with 90° hooks and insufficient anchorage length;

(f) Insufficient anchorage length of longitudinal beam reinforcement (without hooks);
(g) Insufficient lap splice length (often 100% spliced reinforcement at one floor);
Similar deficiencies in reinforcement detailing of RC frames were observed in other earthquakes, such as the 2015 Nepal earthquake (magnitude 7.7). In many cases, RC columns were characterized by small cross-section and inadequate reinforcement detailing. As a result, these columns experienced shear failure, and infill walls acted like load-bearing walls for resisting effects of gravity loads and seismic forces (Brzev et al. 2017).

Beside inadequate reinforcement detailing, the authors also observed examples of good practice. Fig. 12a) and Fig. 12b) show minor damage in RC columns with small tie spacing of ties In the case of the columns shown in Fig. 12a, the ties had 8 mm diameter and were placed at 7.5 cm spacing, which is less than required by KTP-N.2-89 (1989).

5.7 Pounding

Several buildings suffered minor damage in the earthquake due to pounding, which was caused by insufficient size, or absence of seismic gaps, as well as differences in storey heights. Fig. 13a) shows a 5-storey RC frame building located near the fire station in downtown Durrës. The building had 3×2 rectangular columns arranged in a regular grid and infill walls constructed using concrete blocks on all sides at the ground floor level. The building experienced pounding damage due to proximity to a neighbouring masonry building and insufficient seismic gap. The pounding caused permanent (residual) deformations of RC building after the earthquake. Minor damage was also observed on buildings in other cities, e.g. Fushë-Krujë and Krujë (Figs. 13b and 13c, respectively).

6. Non-structural Damage In Cast-in-place Rc Buildings Due To The 2019 Albania Earthquakes

Damage of non-structural building components in cast-in-situ RC buildings exposed to the November 2019 earthquake was more widespread than structural damage. This section provides an overview of damage patterns, failure mechanisms and consequences of collapse of non-structural components on the building functionality of the buildings.

6.1 Masonry infills in RC frame structures

All cast-in-place RC framed buildings exposed to the 2019 Albania earthquakes have masonry infill walls, both in the form of exterior (façade) walls, and interior walls separating adjacent rooms. Large number of mid- and high-rise cast-in-place RC buildings in the earthquake affected area, especially in Durrës, built since the 1990s have masonry infills. Masonry infill walls have been widely used in Albanian buildings due to availability of masonry materials (clay bricks and modular blocks) and masonry construction skills. Also, masonry has additional advantages, such as durability, excellent thermal properties and fire resistance. Masonry infills were usually treated as non-structural elements of RC framed structures in Albania and other countries, however several research studies have shown that their stiffness significantly contributes to the overall structural stiffness and changes the dynamic characteristics of an RC frame structure (Kappos and Ellul 2000; Kose 2009; Ricci et al. 2011; Asteris et al. 2015). As a result, infill walls are effectively components of a lateral load resisting system in these buildings and resist seismic effects. Unfortunately, it is a common practice to ignore the effect of masonry infills in seismic design of RC building, which has resulted in inadequate seismic performance of RC frame structures with masonry infills in moderate and severe earthquakes, e.g., Izmit, Turkey (1999); Bhuj, India (2001); Boumerdes, Algeria (2003), Gorkha, Nepal (2015) and Tehuantepec, Mexico (2017) (Braga et al. 2011; Manfredi et al. 2014; De Luca et al. 2014; Godínez-Domínguez et al. 2021). In some cases, RC buildings experienced severe damage or collapse due to the presence of infills which were not accounted in seismic design; however, in many cases RC buildings did not experience significant structural damage but infill walls experienced damage or a complete collapse, as observed in the area affected by the November 2019 earthquake. It is important to point out the influence of infills on the global seismic behaviour of the entire structure and structural damage, which was described in Section 5. This section is focused on documenting the damage of masonry infill walls in cast-in-place RC buildings.

The authors observed during the reconnaissance visit that many RC buildings did not experience significant structural damage but had to be vacated due to extensive damage of masonry infills and partition walls. Fig. 14 illustrates typical damage in masonry infills, characterized by extensive cracking, while the RC structure remained undamaged. Damage of masonry infills in mid- to high-rise RC structures was widely spread in the Durrës municipality, but similar damage was also observed in other urban areas, including Fushë-Krujë, Krujë (Fig. 13c), and the Bubq village.

Extensive damage of masonry infills in the November 2019 earthquake can be attributed to excessive flexibility of RC frame structures and significant lateral drift demand (see Section 5.2), which caused in-plane damage of the infills. A typical damage pattern was in the form of diagonal (X-shaped) cracks (Fig. 15). Another characteristic in-plane damage pattern observed after the earthquake is bed-joint sliding shear failure along the mortar bed joints, which in some cases caused falling of the central portion of the wall (Fig. 16).

In many cases, masonry infills experienced out-of-plane damage due to distributed inertial forces perpendicular to the infill surface which are induced by spectral accelerations. The out-of-plane damage or failure of masonry infills was also observed after the November 2019 earthquake (Fig. 17). It is expected that in some cases the failure of infills in the building entrance area prevented or disrupted the evacuation from these buildings during and immediately after the earthquake (Lu et al. 2020). Out-of-plane infill failure is usually characterized by tilting of an infill like a rigid body (Fig. 17 and 18).This occurs due to a loss of contact between the frame and the wall.

It has been observed after the November 2019 earthquake that infill damage was often most pronounced at the lower storeys, and was often accompanied by partial or total infill failure (Fig. 17b); this is similar to observations from past earthquakes in other countries (Braga et al. 2011; Lu et al. 2020; Godínez-Domínguez et al. 2021). The out-of-plane failure of infills at the lower storeys may seem unusual since maximum horizontal accelerations are amplified over the building height. From a simplified perspective, a higher extent of infill damage is expected at lower storeys due to larger in-plane interstorey drifts of the frame, however higher damage due to out-of-plane loading is expected at upper storeys. However, it was observed after the November 2019 earthquake that large number of buildings experienced out-of-plane infill damage at the lower storeys, while infill walls at the upper storeys remained intact (Figs. 14, 17, and 19). This can be explained by the fact that during a seismic event, infill walls are exposed to simultaneous in-plane and out-of-plane earthquake shaking. Damage of infills due to in-plane lateral drifts of RC frame causes their vulnerability to out-of-plane seismic effects, which is illustrated in Fig. 21. Masonry infills are traditionally constructed by filling a gap between the infill and the frame with mortar; however, mortar filling gets crushed and falls out due to in-plane movement, as shown in Fig. 18; this makes infill walls vulnerable to damage or failure due to the out-of-plane earthquake shaking (Butenweg et al. 2019). Therefore, it is necessary to take into account the interaction of the in-plane and out-of-plane load. It should be also noted that out-of-plane failure of infills can occur without previous in-plane damage. This happens under simultaneous in-plane and out-of-plane action, when in-plane frame deformation causes loss of contact between frame and infill resulting in infill collapse when even small out-of-plane load acts at the same time. Unfortunately, only a few studies have been conducted on the topic of combined loading action (Butenweg et al. 2019; Kadysiewski and Mosalam 2009; Yuen et al. 2016; Marinković 2018).

In addition to the damage of exterior infills (along the façade), similar damage patterns were observed inside the buildings (Figs. 15, 20), where infill collapse caused a risk from injuries and prevented evacuation from the buildings by blocking the corridors. It should be pointed out that out-of-plane infill failure could also potentially harm individuals outside the building (Figs. 17 and 19).

6.2 Exterior (façade) unreinforced masonry walls

Beside masonry infill walls, exterior (façade) unreinforced masonry walls were also extensively damaged (Fig. 21, 22 and 29). These walls were constructed using hollow clay blocks with horizontally aligned holes, and located in cantilevered portions of buildings at the perimeter (Fig. 19a). These walls were supported on the cantilevered portions of floors. These walls are commonly used in RC buildings in Albania. The extensive damage of similar walls was also observed in the 2015 Gorkha, Nepal earthquake (CAEE 2017). Seismic behaviour of these walls can be improved by providing RC vertical elements at the wall end and intersections. The extensive damage of these cantilever walls was due to horizontally aligned holes in clay blocks, permanent floor slab deflections due to gravity loads and lack of connection of these walls with the structural system.

6.3 Stairs and elevators

Elevators and stairs are critical non-structural elements because they enable evacuation from damaged buildings immediately after an earthquake. Experiences from past earthquakes have shown that the most frequent type of elevator failure is counterweight derailment (Suarez and Sing 2000), which is caused by earthquake-induced lateral forces and displacements (Filiatrault et al. 2001). In an 8-storey RC building visited by the authors in Fushë-Krujë, the elevator remained functional despite noticeable cracking of the surrounding masonry infill walls (Fig. 23). Additionally, large windows (façade glazing) on the ground and first floor remained intact, which indicates that the cracks in the masonry infills developed at drift levels lower than the ones that would cause elevator malfunction or cracking of glazing.

Even though stairways are usually not considered in seismic design of buildings, past experiences have shown that an interaction of stairways with the primary structure can cause severe damage both in the primary structures and in the stairways, thus hindering post-earthquake evacuation of buildings and restoring their functionality (Roha et al. 1982; Li and Mosalam 2013; Stepinac et al. 2021). Examples of primary structural damage, e.g., short-column effect, due to the interaction with the stairways were presented in Section 5, while this section is solely focused on the stairway damage. Failure of stairway enclosure (Fig. 24) in flexible multi-storey RC buildings with masonry infills was observed in Durrës. The debris of damaged masonry infills which experienced out-of-plane failure blocked the stairs in several RC buildings (Fig. 23b and Fig. 24b). This type of damage was observed in multi-storey RC buildings, where large RC frame deformation or insufficient connections between the RC frame and the infill walls caused the masonry infills to separate from the RC frames and fall out, thereby blocking the stairway. Similar damage and failure patterns were also observed after the 2008 Wenchuan earthquake (Li and Mosalam 2013).

6.4 Building installations

Falling out of severely damaged masonry infill walls in 12-storey RC frame building in Durrës (Fig. 14) caused damage to the building piping and installations (Fig. 25). As non-structural damage was concentrated on the lower floors of the buildings, tenants at the upper floors could continue to occupy their apartments for shelter purposes. However, due to the damage of building installations at the lower floors, some of the apartments at the upper floor levels did not have access to the necessary infrastructure (e.g., electric power, potable water), hence these apartments were not fully functional after the earthquake (Blagojevic et al. 2022).

Table 2
Main characteristics of the case study buildings.

	12-storey building	**4-storey building**
Seismic design code	KTP-N.2-89 and Eurocode 8 (partially)	KTP-N.2-89
Year of construction	2016-2018	2002
Soil category	III (KTP-N.2-89), D or S1 (Eurocode 8)	III (KTP-N.2-89), D or S1 (Eurocode 8)
Structural system	RC moment frame with shallow beams	RC moment frame with shallow RC beams
Structural regularity	Mostly regular in plan and irregular in elevation (blocks separated by seismic joints)	Mostly regular in plan and irregular in elevation
Building height	39.5 m and 45.7 m (penthouse)	12 m and 14 m (penthouse)
Storey height	Ground floor 4.85 m, other floors 3.15 m	Ground floor 4.0 m, other floors 3.15 m
Building plan dimensions	33.7 m x 23.1 m (typical block)	18.3m x 11.3m
Foundations	Cross beam foundation system with cross-sectional dimensions bxh=120x150cm	Footings (2 m × 2 m) 1.2 m thick + tie beams (cross section 0.25 m × 0.7 m), at 2.7 m underground
Basement available	Yes	No
Slabs and beams	Cast-in-place, 30 cm thick, two-way ribbed slab with polystyrene infill. Beam depth 30 cm.	Cast in place, 20 cm thick, two-way ribbed slab with polystyrene infill. Beam depth 20 cm.
Materials (based on design)	Concrete C20/25 (cylinder compressive strength 20MPa), steel yield strength 450 MPa (deformed steel)	Concrete C25/30 (cylinder compressive strength 25MPa), steel yield strength 240 MPa (mild steel)
Column spacing	Ranges from 5.6 m to 7.9 m	Ranges from 3.0 m to 4.5 m
Column cross-sectional dimensions	1.2×0.6m, 1.0×0.5m, 0.8×0.4m	0.3×0.3m, 0.25×0.25m
Column reinforcement	Longitudinal reinforcement ratio ranges from 1.2 to 1.3%, Ø8 mm ties at 10 cm and 20 cm spacing	Longitudinal reinforcement ratio approx. 3.0%, Ø8 mm ties at 10 cm and 15 cm spacing
Beam sizes	Width ranges from 0.8-1.2 m, depth = 0.3m	Width×depth = 0.5m×0.2m

	12-storey building	4-storey building
Beam reinforcement	Longitudinal reinforcement ratio approx. 1.0 %, with 30 cm critical regions and stirrups Ø8 mm at 6 cm and 16 cm spacing	Longitudinal reinforcement ratio approx. 4.0 %, with 120 cm critical regions and stirrups Ø8 mm at 10 cm and 20 cm spacing

7. Twelve-storey Case Study Rc Building In Durrës

7.1 Twelve-storey case study RC building in Durrës

As mentioned earlier, 3 blocks of the 12-storey building are structurally independent (Fig. 26), and are separated by means of seismic joints which are 10-15 cm wide at lower levels and approximately 30 cm wide at the top. This is not fulfilling the requirements from KTP-N2-89 (1989), since based on the seismic analysis a seismic joint at the top should be 60-70 cm. The blocks are supported by crossed-beam foundation system followed on top by RC slab. These blocks are generally similar, hence a typical block with floor plan shown in Fig. 27 is discussed here. As a result of different storey heights for the ground floor and upper floors (see Table 2) and the absence of infills at the ground floor level, this building has an irregularity in elevation. There is also an issue with the column layout shown in Fig. 27, which has been recognized as a weakness in similar buildings affected by the November 2019 earthquake.

A 3-D linear elastic model of the building block was developed to study dynamic characteristics of the building. The first three mode shapes are shown in Fig. 28a). As expected, the structure is very flexible, with the fundamental period on the order of 3.0 sec. It is expected that the dynamic properties would be different - fundamental period would have been smaller if the numerical model had taken into account the effect of masonry infills. In addition, the model did not include the effect of soil – structure interaction, which could result in an increase in the fundamental period. The mode shapes are fairly regular - the first two modes are translational while the third one is torsional.

Eurocode 8 Type-1 elastic response spectrum with 5% damping and a_{gR}=0.15g for soil type D (Fig. 28b) is used for response spectrum analysis. The same spectrum is used for both orthogonal directions ($\pm E_{Edx} \pm 0.3E_{Edy}$ and $\pm E_{Edy} \pm 0.3E_{Edx}$). CQC is used for modal combinations, taking into account 12 mode shapes, producing modal mass contribution of 95%. The mass of the structure is calculated based on the combination (100% permanent load + 30% variable load) and no stiffness reduction is used for the structural elements (although 50% of reduction is suggested in Eurocode 8). Note that the seismic parameters were not considered according to the codes, for example behaviour factor of 1.0 was assumed for analysis purposes. The results show that the distribution of bending moments in the columns (Fig. 28c) is not typical for moment frames, since the contraflexure point is not located near mid-storey height; instead, the distribution resembles the response of shear wall systems. This result can be explained by the effect of flexible beams. As a result, the system behaved like a flat slab structure without adequate lateral bracing in the form of shear walls. This trend can be also observed in Fig. 28d), since the shape for fundamental mode is similar to cantilevered members (such as shear walls). The roof displacements obtained from the analysis were in the range from 25 to 30 cm (corresponding to 0.7% total drift ratio), which are very close to the size of actual seismic gap. The inhabitants reported strong noise during the earthquake, which could be explained by pounding of building blocks, and damage to masonry infills was observed in the vicinity of the joints; however, insignificant pounding damage of RC structural elements was observed after the earthquake.

The above results generally agree well with the post-earthquake field observations. Masonry infills in this building experienced significant damage, which was mostly concentrated within the bottom portion (lower 5 storeys) (Fig. 29). Based on the analysis results it can be concluded that excessive infill damage can be attributed to a significant flexibility of this system, which resulted in large lateral displacements and interstorey drifts during the earthquake. The flexibility of the structure is due to the absence of RC shear walls, which was compounded by the presence of shallow floor beams. The infill damage was also caused by combined in-plane and out-of-plane seismic effects, which was especially pronounced at the lower storeys. Large interstorey drifts caused damage of infill and partition walls and/or their detachment from the surrounding frame, making them vulnerable to out-of-plane seismic effects. In addition, a lack of RC confining elements (tie-columns or horizontal belts) and placement of exterior masonry walls offset with regards to the column gridline (for example, at the balconies) made these walls more susceptible to failure (Fig. 29). In addition, excessive beam deflection was observed at the ground floor level (Fig. 30a). While it is unclear whether these large deflections were caused by the earthquake or were due to gravity loading, it is possible that they contributed to degradation of bond between the masonry infills and the RC adjacent frame members.

Besides the widespread damage observed in masonry infill walls, signs of structural damage were observed in RC members. A few examples illustrate damage of columns (Fig. 30b) and beams (Fig. 30c). The damage was in the form of inclined cracking caused by shear and torsion, and spalling of concrete cover. The damage in RC frame members can be attributed to significant flexibility of this building.

7.2 Four-storey case study RC building in Durrës

The building experience damage in masonry infills in the September 2019 earthquake, and it further damaged in the November 2019 earthquake while the repair works were still in progress. Fig. 31 shows damaged masonry infills at the ground floor level. Damage due to the September 2019 earthquake was concentrated at the ground floor level and around the staircase. Note that the building reportedly experienced differential settlements before the 2019 earthquakes, which could be attributed to soft soil conditions.

An important characteristic of this building is that it did not meet the KTP N.2-89 (1989) requirement related to the minimum beam depth (30 cm). Instead, the beams were only 20 cm deep (see Table 2). The building has a glass façade and masonry infill and partition walls in the interior and reduced amount of infills at the ground floor compared to the upper storeys. Furthermore, infills at the ground floor level were distributed in unsymmetrical manner, leading to a potential plan irregularity. A comparison of the original design specification with in-situ tests and measurements showed that the original design was generally followed. Unfortunately, concrete compressive strength was found to be significantly lower than specified in the design. The tests on cored cylinders showed compressive strength of approximately 13 MPa, which is significantly lower than the 25 MPa value specified in the original design (see Table 2).

Figure 32 Results of the response spectrum seismic analysis for the 4-storey case study building: a) characteristic shapes for translational and torsional vibration modes, and b) fundamental mode shape and interstorey drift ratios

A linear elastic model was developed for this building based on the available data, neglecting the contribution of masonry infill walls and soil-structure interaction. Like in the case of 12-storey building, the response spectrum analysis was performed using the same input parameters (Fig. 28b). The results of modal analysis are shown in Fig. 32a. Even though the building has only four storeys, its fundamental period is quite high (approximately 1.5 seconds), which points out to a significant flexibility of this building. Maximum interstorey drift ratios obtained from the analysis are in excess of 1.5%, which is higher than the maximum drift of the 12-storey building (Fig. 32b). Besides very shallow RC floor beams, the columns were also characterized by a cross section which was smaller than or equal to 0.3 m × 0.3 m (see Table 2), which contributed to excessive flexibility of the structure. Based on the response spectrum for the Durrës station shown in Fig. 28b, fundamental period for this 4-storey structure (T_1=1.53s) is within the range of high spectral accelerations, which contributed to a higher seismic demand in comparison to the 12-storey building (T_1=2.98s).

Large interstorey drifts and high spectral accelerations caused damage of both masonry infill walls and structural RC members in this building. Structural damage was concentrated at the ground floor level, whereas damage to masonry infills was more extensive at the ground floor level and the first floor. The observed damage in RC columns was in the form of shear and flexural cracks, as well as spalling of concrete cover (Fig. 33a).

Damage was also observed in RC beams and slabs (Fig. 33b), mostly in the form of cracks at the bottom surface. In some cases, severe damage was also observed near the staircase at the connection between the stairs and the horizontal RC members (beams and slabs), as well as within the staircase (Fig. 33b). Due to the flexibility of columns and beams, it is likely that stiff staircase structure had contributed to the lateral load resistance before it experienced damage. Finally, infill walls at the ground floor level were severely damaged (Fig. 34), and the damage was more extensive compared to that caused by the September 2019 earthquake.

8. Conclusions And Recommendations

In September and November 2019 Albania was affected by the strongest earthquakes that occurred in the last 40 years, and at the same time the first damaging earthquakes since the official seismic design code KTP-N.2-89 (1989) was published in 1989. This paper discusses the impact of these earthquakes on the cast-in-place RC buildings in Albania. This section contains relevant conclusions based on the authors' reconnaissance study and recommendations for enhancing resilience of existing and new RC buildings in Albania.

Conclusions

- Based on the seismic hazard studies performed after the 2019 earthquakes, it was observed that the November 2019 earthquake caused rather high spectral accelerations within the fundamental period range from 0.5 to 1.5 sec, corresponding to dynamic characteristics of modern mid- and high-rise RC buildings in Albania. Significant vertical accelerations were recorded in Durrës, in the vicinity of the epicentre.

- Statistical analysis of 2,593 mid- and high-rise RC buildings in the Durrës municipality was performed to study the extent of damage as a function of the building height and year of construction. Out of these buildings, 1,728 buildings were 3-5 storey high while 865 buildings are taller (6 storeys and up). More than 80% of RC buildings considered in this study were constructed after 1990. It was estimated that 42% of all damaged 3- to 5-storey RC buildings and 35% of taller RC buildings experienced minor to moderate damage. A relatively small fraction of these buildings experienced severe damage or collapse, that is, 7% of 3- to 5-storey RC buildings and 3% of taller RC buildings.
- Major social, economic, and political changes occurred in Albania in the early 1990s, soon after the seismic design code KTP-N.2-89 (1989) was published in 1989. It is expected that majority of buildings affected by the 2019 earthquake were designed in partial or full compliance with the Albanian code, however some taller buildings were designed in partial compliance with the pertinent Eurocodes. Finally, some of the affected buildings were not designed and/or constructed in compliance with the building codes (non-engineered buildings).
- Non-engineered RC buildings, mostly low-rise housing (single-family dwellings or smaller apartment buildings), suffered the most extensive damage due to the 2019 earthquakes. A significant fraction of the damaged buildings were designed according to the KTP-N.2-89 (1989) code, but the provisions were not fully implemented in the design, particularly as related to the size of seismic joints, cross-sectional dimensions of shallow RC floor beams, and the connections of façade masonry walls to the RC frame structure.
- It was observed that mid-rise RC buildings experienced significant structural damage or collapse, while high-rise RC buildings experienced primarily non-structural damage.
- The authors observed a few types of structural irregularities in mid-rise RC frame buildings with masonry infills. In most cases, irregularities were related to building elevation and were caused by a variation in lateral stiffness over the building height. In some cases, absence of masonry infills at open lower storeys caused a “soft storey“ collapse mechanism, which was characterized by concentrated structural damage or collapse within the open lower portion of the building. In addition, some mid-rise RC buildings had a plan irregularity due to irregular and eccentrically located staircases, which caused extensive damage due to torsional effects.
- Excessive lateral flexibility was a common issue in damaged high-rise RC buildings in Durrës and the surrounding areas. The lateral-force-resisting system in these buildings comprised of RC columns, shallow RC beams and inadequate number or absence of RC shear walls. These designs were partially in compliance with the Albanian seismic design code KTP-N.2-89, which did not contain explicit lateral displacement control criteria.
- The authors observed inadequate reinforcement detailing, substandard quality of construction materials and execution in several RC buildings, which contributed to extensive damage or even collapse of those buildings.
- Significant damage and collapse of masonry infills, which was the predominant type of damage in this earthquake, can be attributed to the excessive flexibility of RC frame structures having high interstorey drifts that posed high in-plane demands in the infill walls. In addition, an interaction of in-plane and out-of-plane seismic actions on masonry infills was the main cause of their substantial damage and/or collapse in the November 2019 earthquake.

- Exterior masonry walls were also significantly damaged in the earthquake. These walls were usually located at the edge of cantilevered portion of the floor slabs, and were constructed using hollow clay blocks with horizontally aligned holes. It is believed that the main cause of damage was a lack of reinforcement and framing at the wall corners in the form of vertical RC tie-columns. It is expected that these walls were subjected to high seismic demand due to combined effects of horizontal and vertical spectral accelerations, which contributed to significant damage, particularly in Durrës, which is located in epicentral area of the November 2019 earthquake, where relatively high vertical accelerations were recorded.
- A case study on two damaged RC buildings located in Durrës included a detailed seismic evaluation, which confirmed that these flexible RC frame systems were characterized by high fundamental period values, e.g., 1.5 s period for the 4-storey case study building. The analysis also showed that the buildings experienced large interstorey drifts, particularly in the lower portion, which can be attributed to an open ground floor and irregular stiffness distribution up the building height. The effect of masonry infills and the resulting irregularities were not considered in the original design.
- Both case study buildings were located in a soft soil area, similar to many other RC buildings in Durrës and the surrounding areas, which resulted in the amplified earthquake effects and contributed to moderate structural damage and heavy non-structural damage in these buildings.
- In the 12-storey case study building, large column cross-sections combined with shallow beams resulted in a cantilever behaviour of RC columns at the bottom floors.

Recommendations

- Albanian government authorities responsible for building regulations need to either revise the current Albanian seismic design code KTP-N.2-89 or adopt Eurocodes as mandatory design codes and ensure their enforcement in practice. For example, Eurocode 8 (EN 1998-1:2005) contains provisions relevant to the causes of damage of RC buildings affected by the 2019 Albania earthquakes, including ductile reinforcement detailing, limiting interstorey drifts, and also requires explicit control of the effect of irregularities in plan/elevation.
- Excessive lateral flexibility of the existing RC structures could be mitigated by providing new RC shear walls or steel braces as a part of seismic retrofit project.
- Flexibility of new RC frame structures with masonry infills could be controlled by increasing column cross-sections and/or by providing RC shear walls. These provisions are expected to reduce lateral drifts in RC frames and the impact on masonry infills. Second option it to modify the masonry infills with the aim of improving their behaviour during earthquakes.
- Seismic design of RC framed buildings with masonry infills need to consider the effect of infills in numerical models in order to take into account an increase of internal forces in the RC frame elements, as well as change of dynamic characteristics of the structure due to the infill-frame interaction.
- Nonlinear seismic analysis of existing RC frame buildings with masonry infills is required to understand their failure mechanisms and inform the seismic retrofitting solutions.
- Seismic behaviour of masonry infill walls can be improved using a few different approaches, such as i) by strengthening existing infills by means of overlays, such as TRM mortar, ii) by increasing energy

dissipation by dividing an infill into several rigid horizontal or vertical panels, or iii) by isolating infills from the frame. According to the first two approaches an infill is a structural element, which must be taken into account in the design. The third approach consists of isolating an infill wall from the surrounding RC frame as a non-structural element; this can be accomplished by leaving a gap between the frame and the infill that would prevent infill-frame interaction. The isolation approach does not require modelling of infills in the analysis process and eliminates the problem of changing the dynamic characteristics of RC structure due to the effect of masonry infills. A gap between RC frame and an infill can be filled with soft material that enables the deformation of the frame without activating the infill and at the same time provides a connection, which will prevent the wall from falling out of the plane. Promising solutions related to isolating masonry infills have emerged in the last few years (Marinković 2018; Marinković and Butenweg 2019) and have a strong potential for future field applications.

- It is very important to reinforce exterior masonry walls and prevent their damage in future earthquakes in Albania. A possible solution is to provide vertical RC elements (like tie-columns in confined masonry structures) at wall corners/intersections.

Declarations

Acknowledgement

Marko Marinković, Ivan Milicević and Svetlana Brzev gratefully acknowledge Serbian Association for Earthquake Engineering (SUZI-SAEE) for sponsoring their reconnaissance visit to Albania in December 2019. Nikola Blagojević gratefully acknowledges the Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich, for providing financial support for the author's reconnaissance visit to Albania in December 2019. Markel Baballëku acknowledges consulting company UTS-01 regarding the design information and material tests results of case study buildings and large scale of rapid assessment data, as well as Ani Verzivolli for its contribution in collecting damaged building data.

Competing interests

Financial support for the reconnaissance visit of a team (Marko Marinković, Ivan Milicević and Svetlana Brzev) to Albania in December 2019, was received from Serbian Association for Earthquake Engineering (SUZI-SAEE). Nikola Blagojević received a financial support from the Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich, for the reconnaissance visit to Albania in December 2019.

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Figures

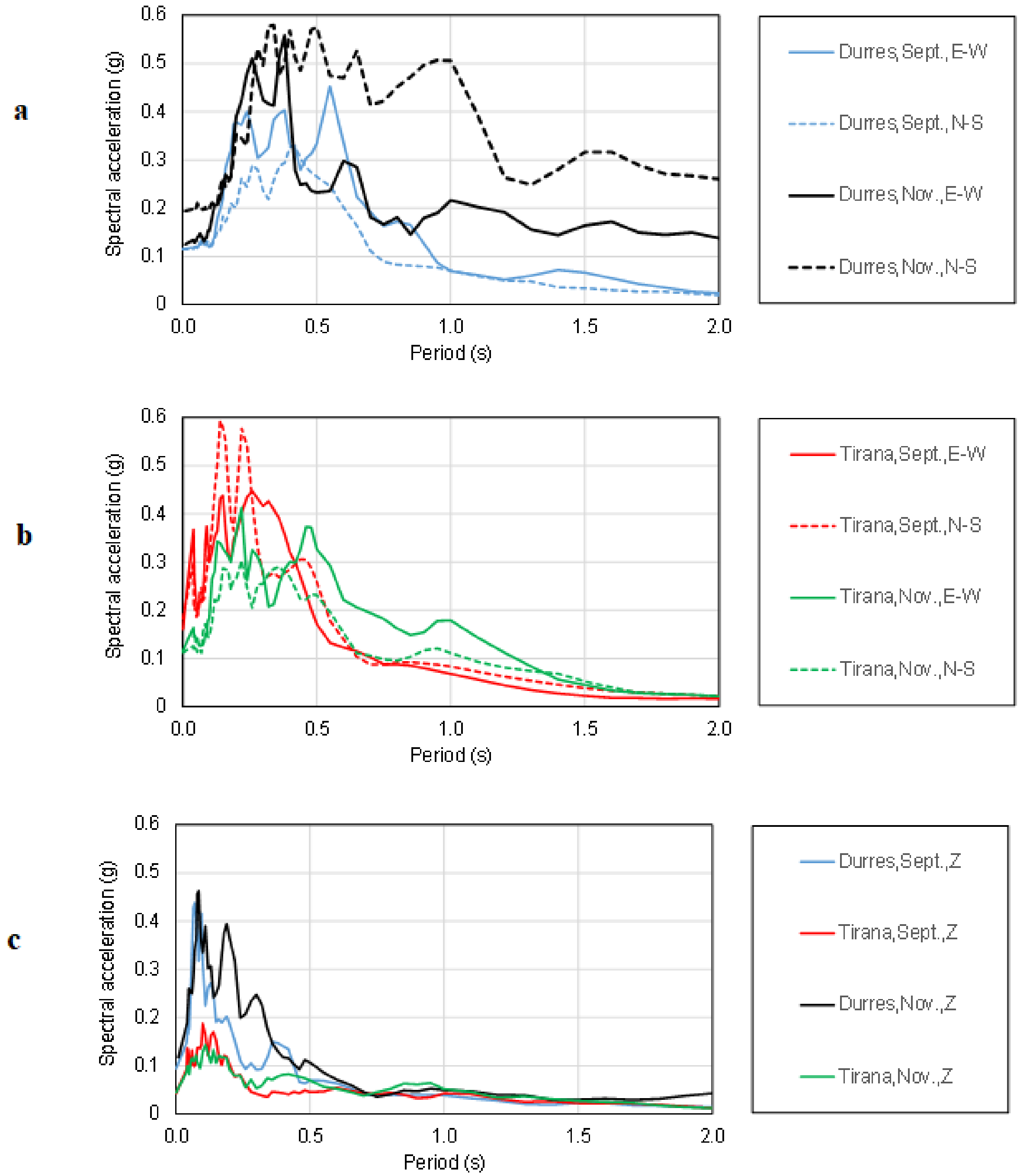


Figure 1

Elastic response spectra of the ground motion records for September and November 2019 earthquakes (5% modal damping ratio): horizontal components (E-W and N-S) a) Tirana, b) Durrës and c) vertical component

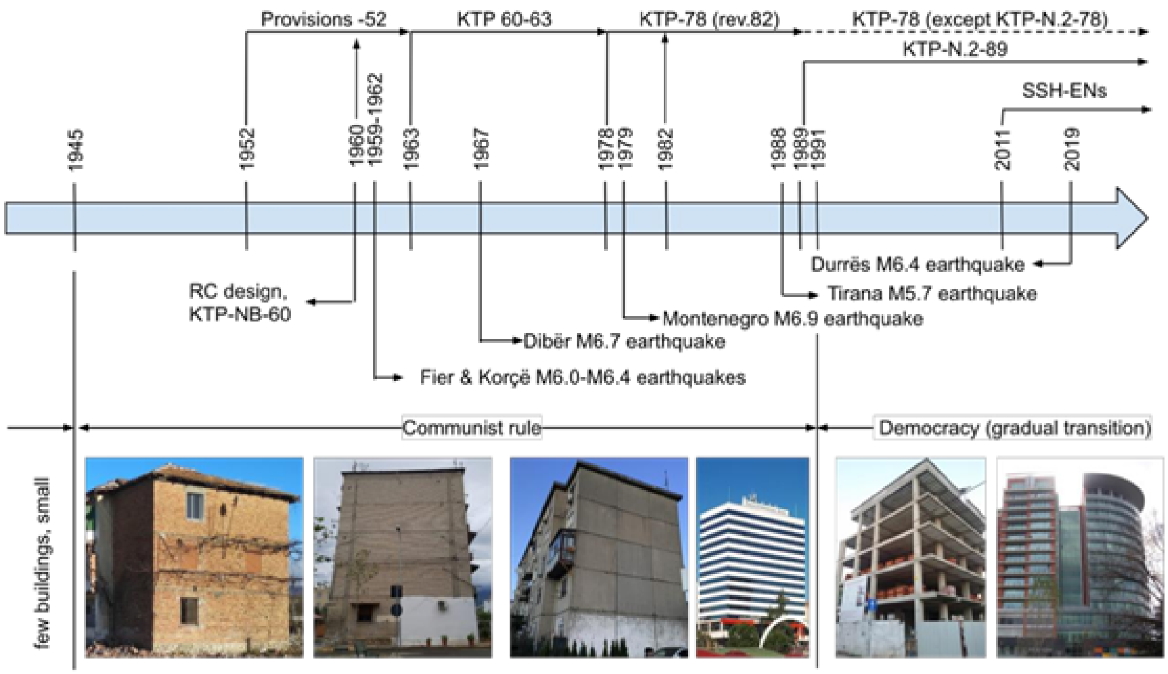


Figure 2

Timeline of design codes, major seismic events, and construction typologies (EERI 2021)

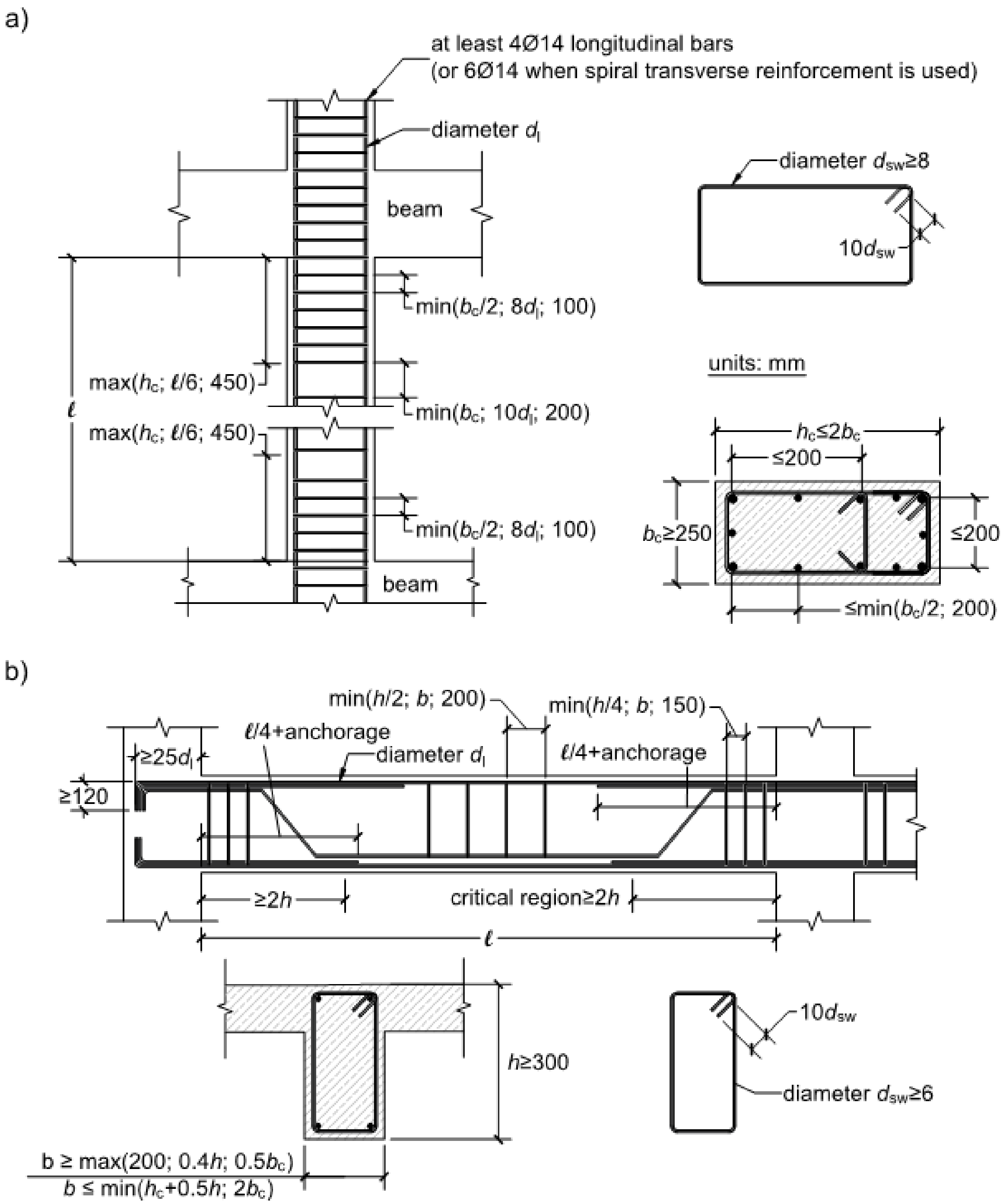


Figure 3

Selected reinforcement detailing provisions of KTP-N.2-89 (1989) for seismic intensity above VIII: a) RC columns and b) RC beams

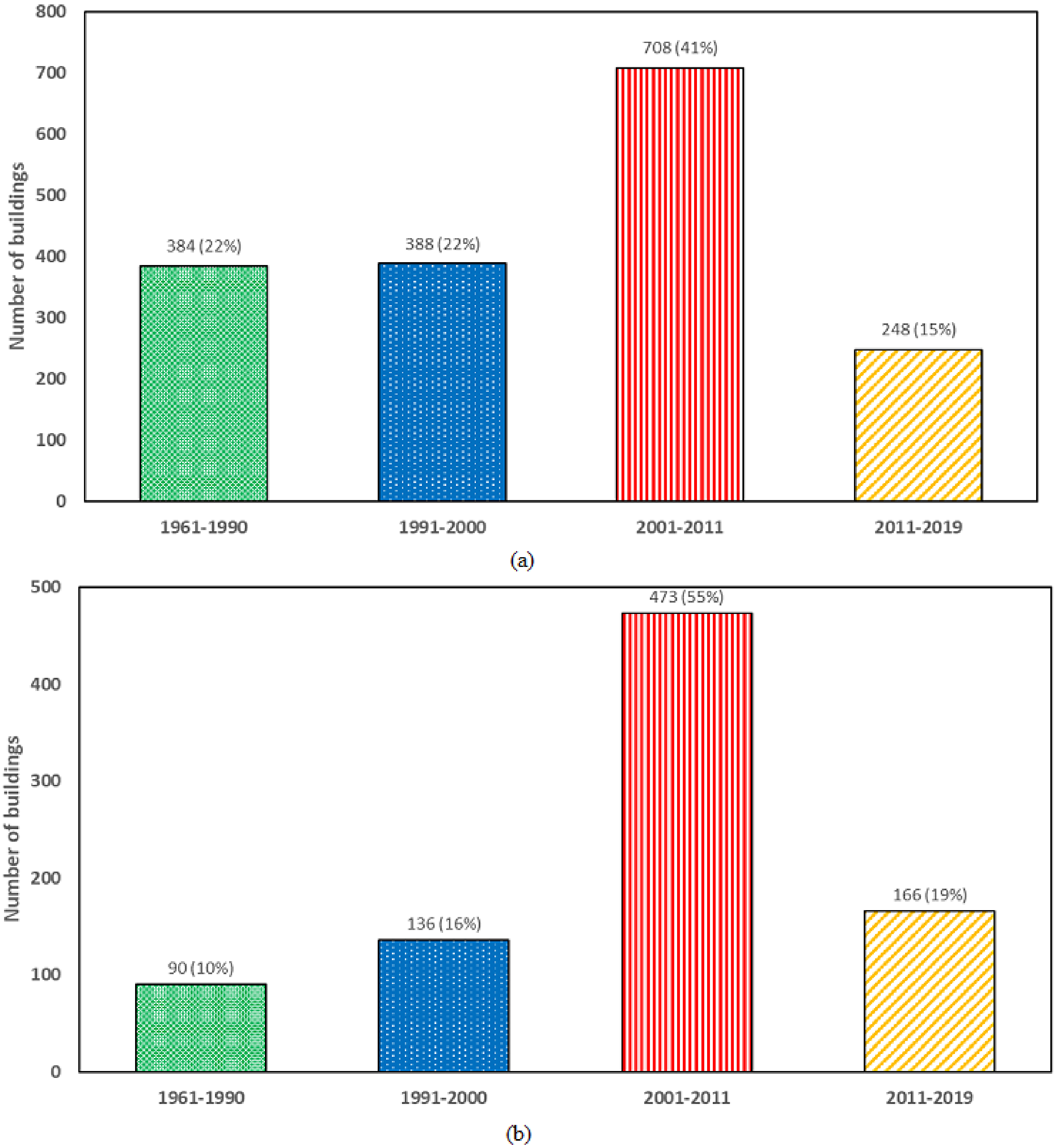


Figure 4

Approximate distribution of RC buildings as a function of the year of construction: a) 3-5 storey buildings; b) taller buildings (height 6 storeys and up). Percentage (shown in brackets) represents a ratio of the number of buildings in the considered category divided by the total number of considered buildings

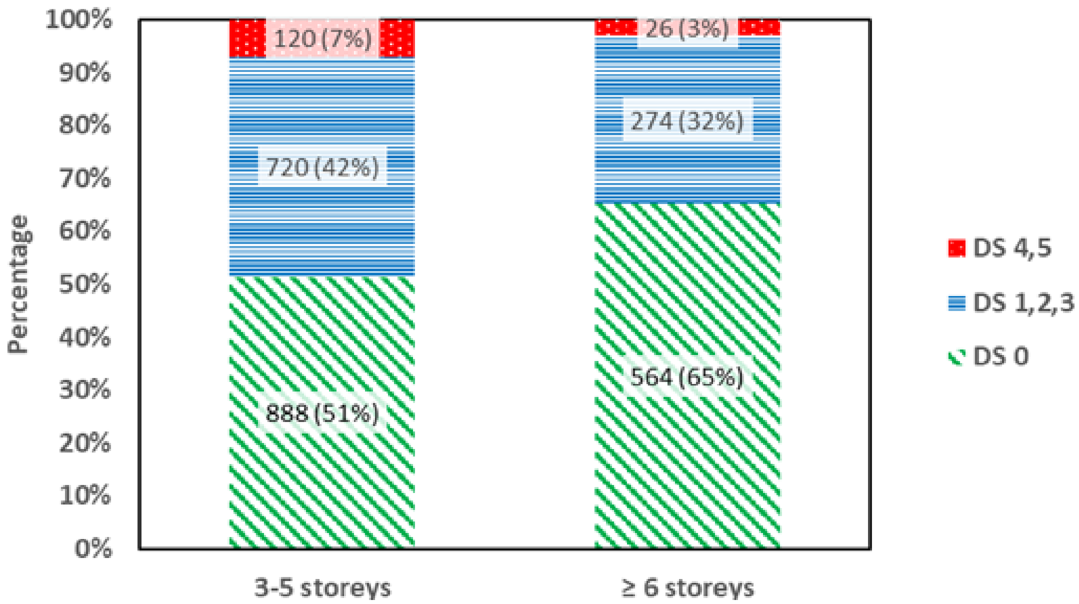


Figure 5

Estimated damage distribution for RC buildings in Durrës municipality

a) b)

Figure 6

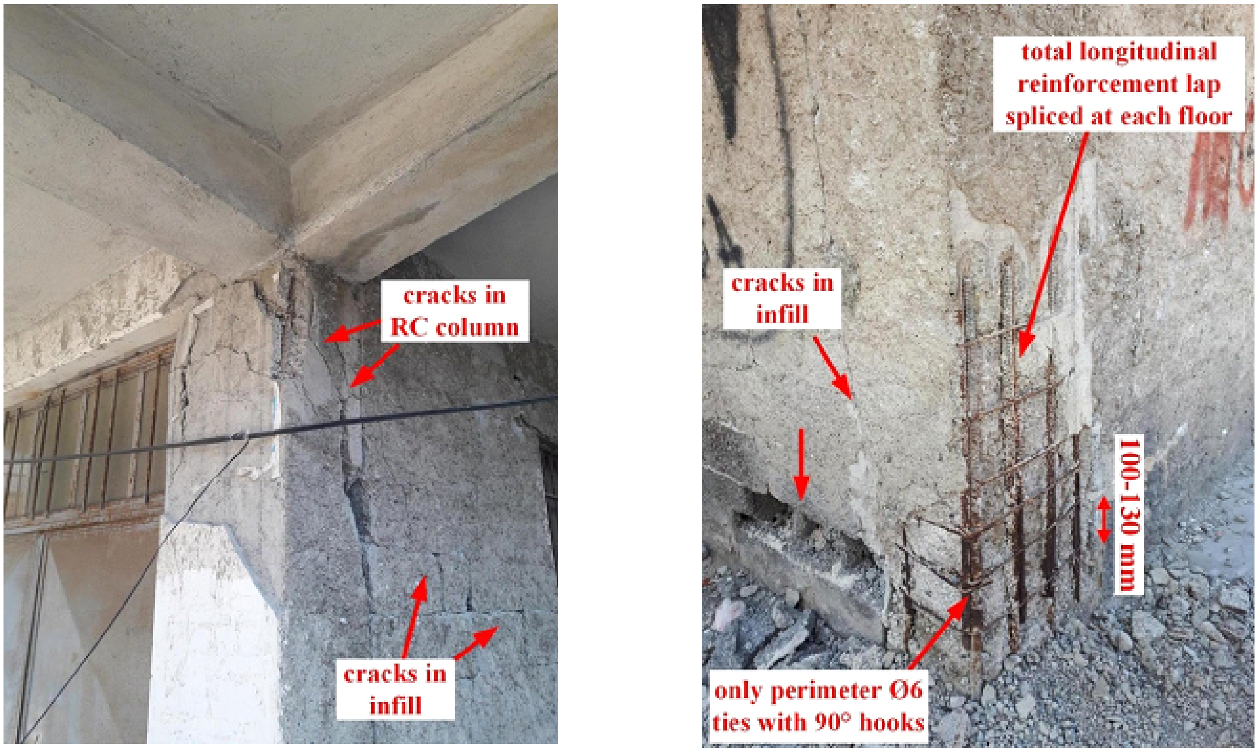
Collapse of Hotel Ljubljana in Durrës due to “soft storey” failure mechanism

a) b)

c) d)

Figure 7

“Soft storey” collapse of a 4-storey house in Thumanë: a) east façade; b) south-west corner; c) south façade; d) north façade



a) b)

Figure 8

RC columns damaged due to stiff infills and frame-infill interaction

a) b)

Figure 9

Examples of damaged RC columns due to „short-column” effect: a) the effect of a partial infill, and b) the effect of a stiff staircase on RC column

Figure 10

Damage of a 7-storey RC building at seaside Durrës: a) east corner, b) S-W façade of the building with severely damaged RC columns, c) floor plan at ground floor level, d) infill damage at N-E façade

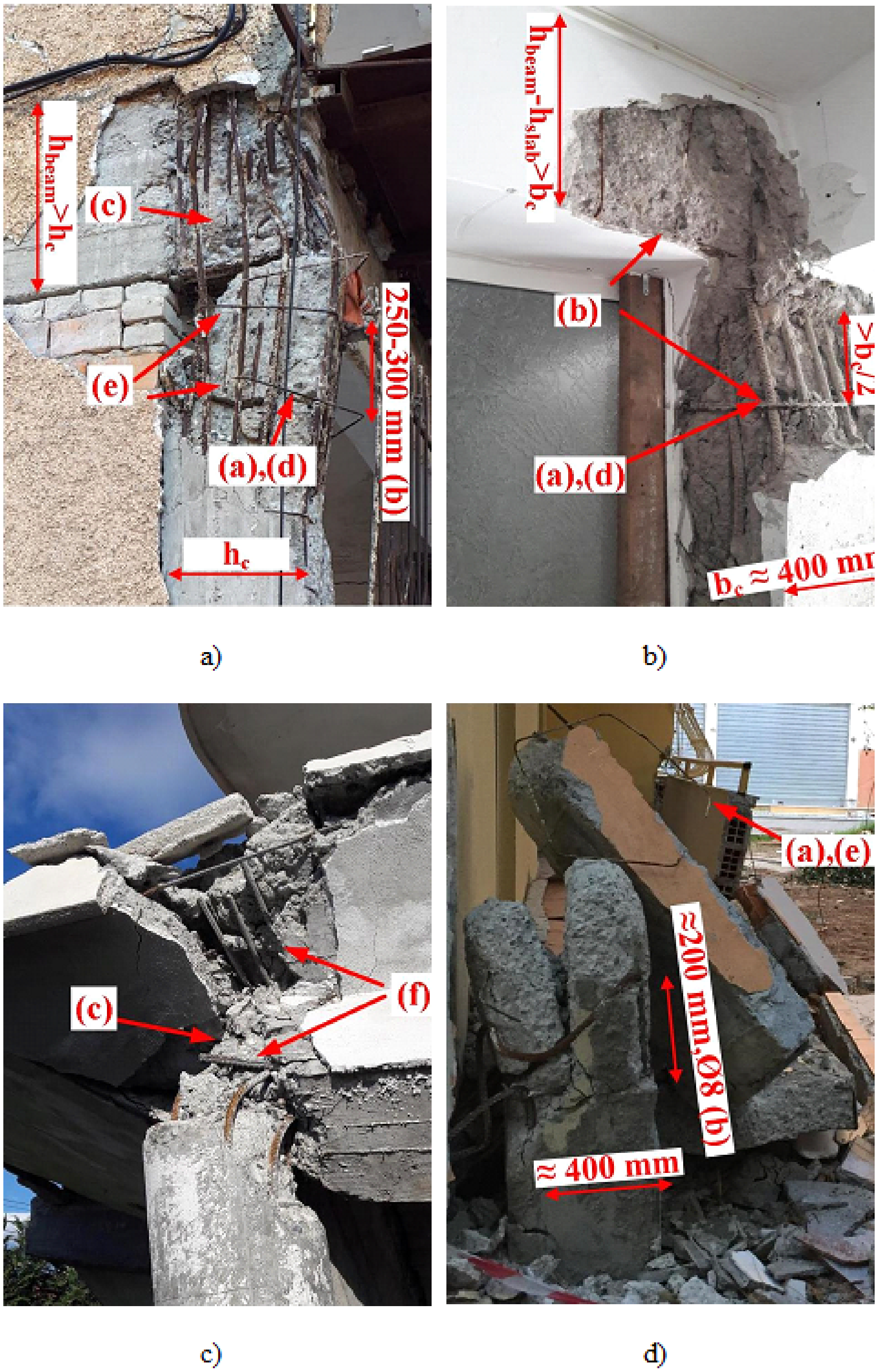


Figure 11

Examples of inadequate reinforcement detailing of RC columns and beams: a), b) buildings in downtown Durrës, c) a 4-storey house in Thumanë, d) a building at seaside Durrës

a) b)

Figure 12

Examples of good reinforcement detailing practice in multi-storey RC buildings constructed after 2010: a) a 12-storey building in downtown Durrës; b) a 6-storey building at seaside Durrës

a) b) c)

Figure 13

Damage in RC buildings due to pounding: a) pounding of a 5-storey masonry and a RC buildings in downtown Durrës, b) pounding of 8-storey and 2-storey RC building blocks in Fushë-Krujë, c) pounding of 3-storey RC buildings in Krujë

Figure 14

Damage and collapse of infill walls in a recently constructed 12-storey RC building in Durrës

a) b)

Figure 15

Diagonal (X-shaped) cracks in masonry infills inside an RC building in Durrës

Figure 16

Damage of a masonry infill wall in the form of bed-joint sliding mechanism and failure of central portion of the wall

a) b)

Figure 17

Out-of-plane failure of infill walls in RC buildings in Durrës: a) infill failure at ground floor of a 10-storey building (note horizontally aligned perforations in the blocks), and b) various stages of damage and collapse of infills at the second storey level of a 6-storey building

a) b)

Figure 18

Damage of masonry infills at a ground floor level of an RC building: a) a loss of connection between RC frame and infills (Nikolić-Brzev et al. 2020), and b) out-of-plane movement (onset of tilting) of an infill wall

Figure 19

Damage and collapse of a) exterior (façade) walls and b) masonry infills due to out-of-plane earthquake shaking in c) 12-storey RC building in Durrës (Lekkas et al. 2019)

Figure 20

Damage of interior masonry infills inside a 12-storey RC building in Durrës: a) damage and partial collapse of infills at the ground floor level (Nikolić-Brzev et al. 2020) and b) heavy damage and collapse of infill walls at the second floor level

Figure 21

Damage of exterior (façade) masonry walls in a 6-storey RC building in Fushë-Krujë

Figure 22

Damage of exterior (façade) masonry walls in a 6-storey RC building in Durrës

a) b)

Figure 23

a) Damaged masonry infill around a functional elevator in an 8-storey RC building in Fushë-Krujë (Nikolić-Brzev et al. 2020) and b) an example of a 5-storey RC building in which out-of-plane failure of masonry infill blocked the stairs (McKenney 2019)

a) b)

Figure 24

Examples of stair damage in the November 2019 earthquake: a) damage stair landing (spalling of concrete), and b) damaged stairway enclosure (collapsed masonry infill walls)

a) b)

Figure 25

Damaged ultilities: a) damaged piping and b) electrical installations in a 12-storey RC building in Durrës

Figure 26

Case study RC buildings in Durrës: a) a map showing building locations; b) exterior view of the 12-storey building; c) exterior view of the 4-storey building; d) a layout of the 12-storey building showing 3 blocks; e) a partial floor plan of the 4-storey building

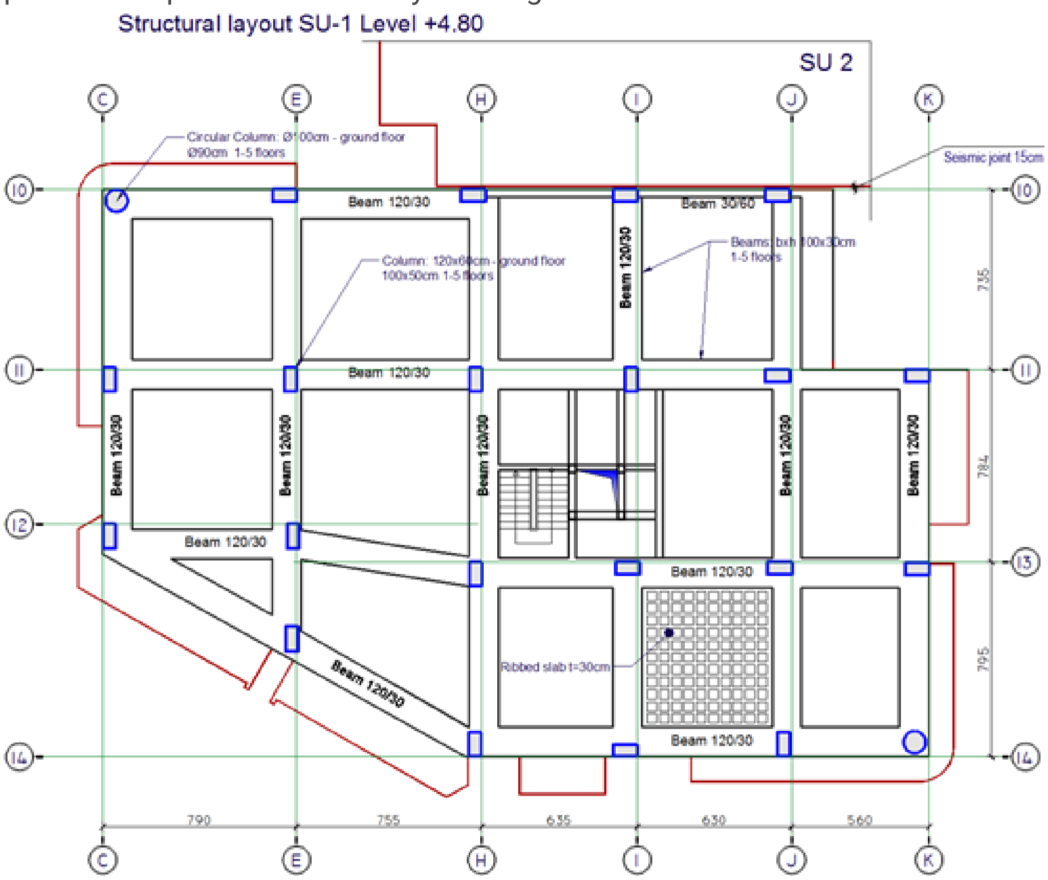


Figure 27

Typical floor plan for a block in the 12-storey building (at 4.8m elevation) (dimensions in centimeters)

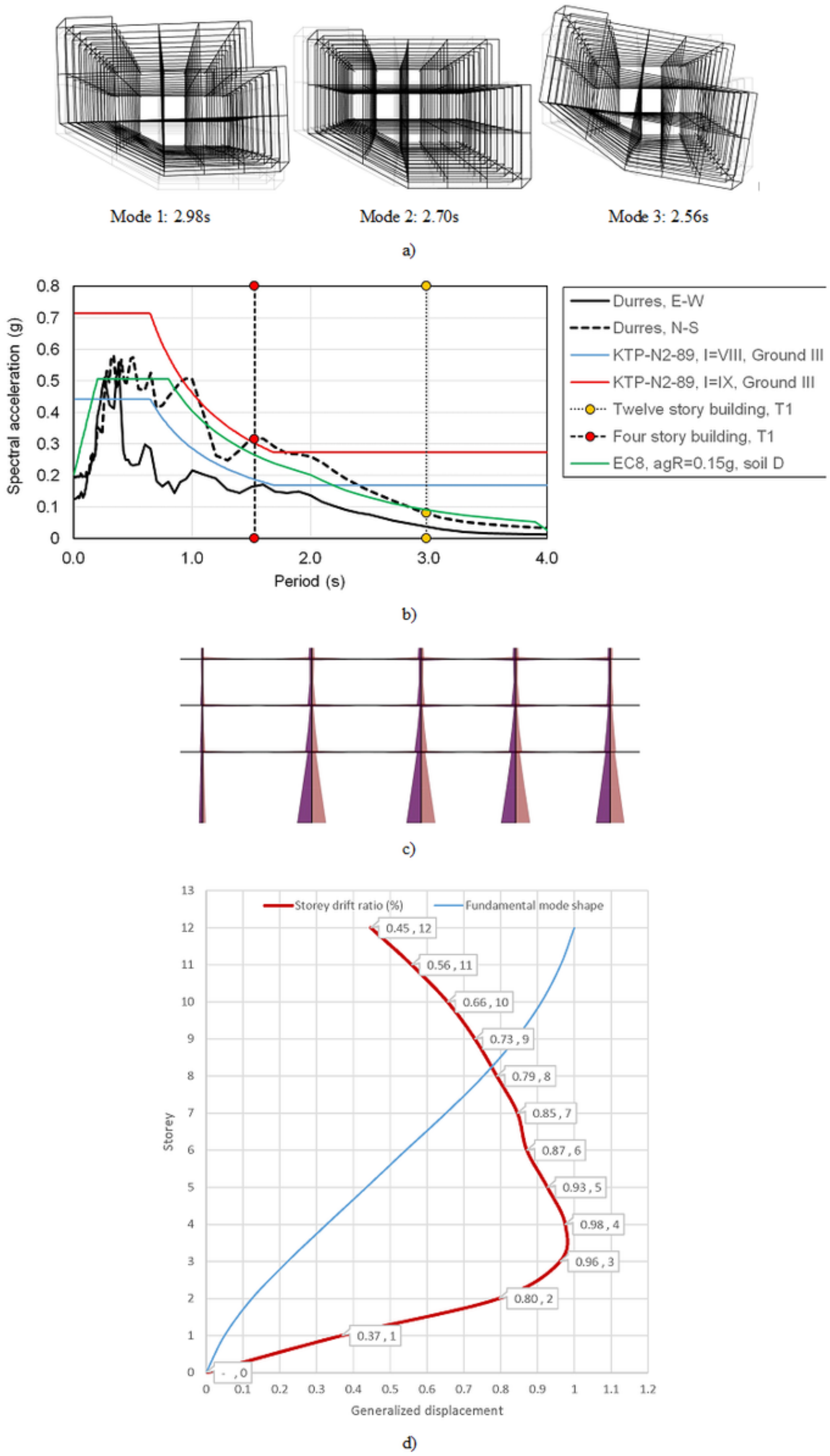


Figure 28

Analysis of the linear elastic model for the 12-storey building: a) characteristic shapes for translational and torsional vibration modes, b) Eurocode 8 spectrum used for response spectrum analysis, c) bending moment diagram for the bottom 3 stories obtained from the response spectrum analysis, d) fundamental mode shape and interstorey drift ratios

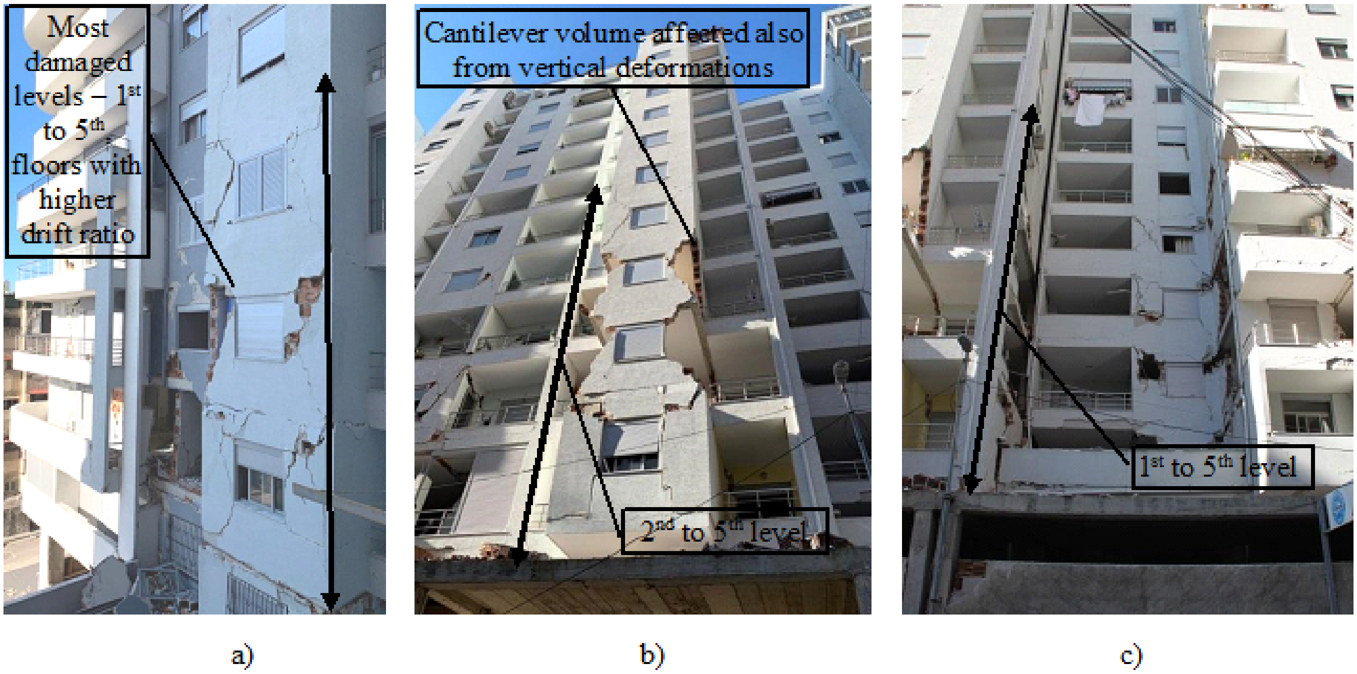


Figure 29

Extensive damage of a), b) exterior (façade) masonry walls and c) infill masonry walls in the 12-storey case study building was limited to the lower 5 storeys

a)

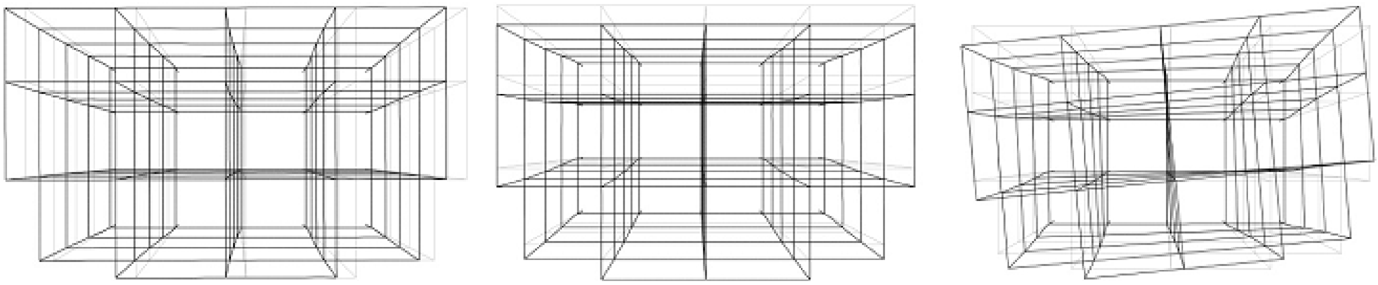
b) c)

Figure 30

Other damage patterns observed in the 12-storey building: a) excessive beam deflections; b) damage of RC columns, and c) inclined cracking on shallow beam around 80cm from the column face

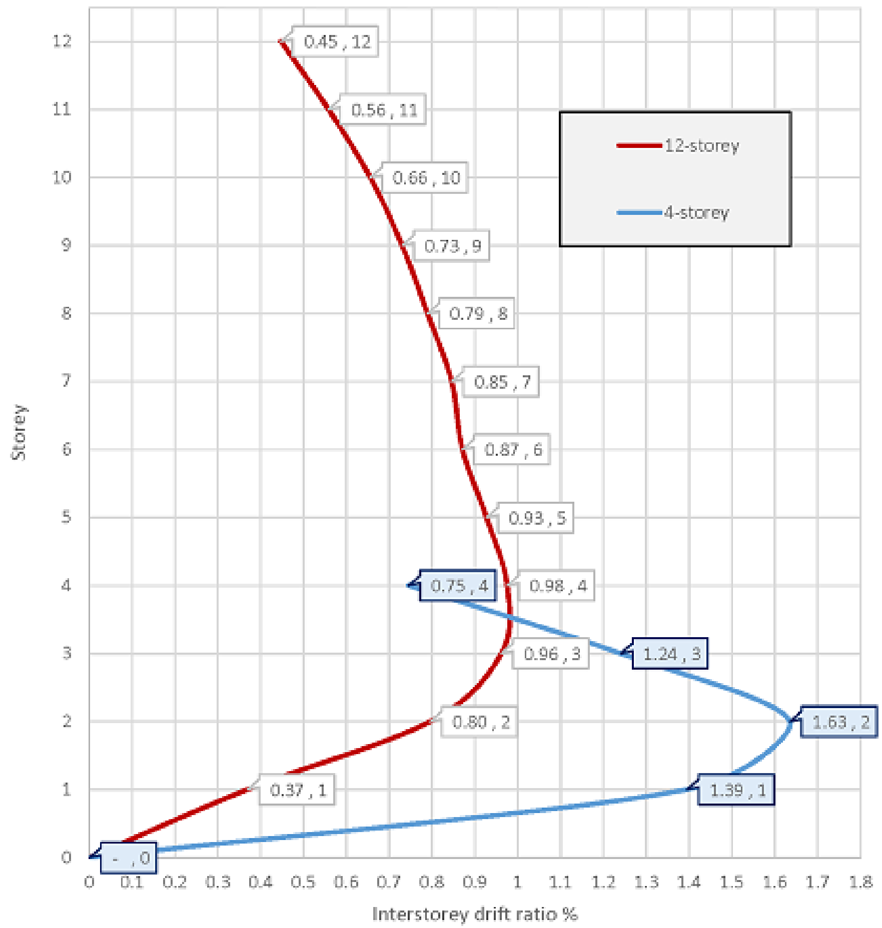
Figure 31

Examples of damaged masonry infills in 4-storey case study building due to the September 2019 earthquake (ground floor level)



Mode 1: 1.53s　　Mode 2: 1.45s　　Mode 3: 1.24s

(a)



(b)

Figure 32

Results of the response spectrum seismic analysis for the 4-storey case study building: a) characteristic shapes for translational and torsional vibration modes, and b) fundamental mode shape and interstorey drift ratios

Figure 33

Observed damage in the 4-storey case study RC building after the November 2019 earthquake: a) columns, b) slabs and c) beams

Figure 34

Damage of infill walls in the 4-storey case study building in Durrës