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VULNERABLE DWELLING TYPOLOGIES IN EUROPEAN COUNTRIES AFFECTED BY RECENT EARTHQUAKES

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SUMMARY

This paper outlines the European contributions to the World Housing Encyclopedia (WHE), with a special emphasis on vulnerable dwellings affected in recent European earthquakes (www.world-housing.net). The WHE currently includes over 90 contributions from 34 countries, making it one of the largest global projects of this type. The present paper briefly reviews the material so far collected for the European continent and analyses specifically two typologies, particularly common in Europe: historic stone and brickwork masonry houses and low engineered reinforced concrete frame apartment blocks. Both typologies have a very high geographical distribution throughout Europe, from Portugal to Romania, and from France to Turkey, although with some substantial regional and quality differences. They certainly represent the most common building types in regions of highest hazard in Europe. The seismic deficiencies of these two typologies together with past and current strengthening strategies will be compared. For masonry buildings a number of different strengthening techniques have been developed and variously implemented in the last 30 years. In some cases the strengthened buildings have been subjected to further shaking, and the performance of the strengthening measures will be critically appraised. In the case of reinforced concrete structures with infill, they have been object of seismic code requirements for decades, but nevertheless, their actual construction overlooks basic rules and technical details, turning them in very fragile and hazardous structures, owing also to higher rates of occupancy. Strengthening criteria and procedures have also been developed in the past 30 years, and common techniques include jacketing by concrete or steel of concrete columns and addition of concrete shear walls. The effectiveness of these measures relies heavily on proper strengthening of the foundations, which might be uneconomically viable for large number of buildings with multi-ownership. More recently strengthening of columns by wrapping of FRP fabric has been proposed, but field implementations are still sparse.

INTRODUCTION

Stone and brickwork masonry buildings with timber floors constitute traditionally the fabric of most urban and rural settlements in Europe. From the beginning of the 20th C these two forms of construction have

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been increasingly replaced, in the areas of greatest seismic risk by reinforced concrete infilled frames. These with a typical height of 4 to 6 storeys have now become the most common housing type in southern Europe. In city centers they are usually built adjacent to each other without any gap, while in more residential areas they are isolated with openings and balconies on all four sides of the block. For masonry buildings a number of different strengthening techniques have been developed and variously implemented in the last 30 years. In some cases the strengthened buildings have been subjected to further shaking, and the performance of the strengthening measures will be critically appraised. In the case of reinforced concrete structures with infill, they have been object of seismic code requirements for decades, but nevertheless, their actual construction overlooks basic rules and technical details, turning them in very fragile and hazardous structures, owing also to higher rates of occupancy. Strengthening criteria and procedures have also been developed in the past 30 years, and common techniques include jacketing by concrete or steel of concrete columns and addition of concrete shear walls. The effectiveness of these measures relies heavily on proper strengthening of the foundations, which might be uneconomically viable for large number of buildings with multi-ownership. More recently strengthening of columns by wrapping of FRP fabric has been proposed, but field implementations are still sparse. An overview of the development of constructional details, damage patterns, vulnerability and strengthening techniques over time is presented in the following. The paper concludes with an overview of the expected vulnerability of the building stock in Istanbul, Turkey, at present the seismic risk hotspot of Europe.

STONE MASONRY BUILDINGS

Stone masonry buildings either in arrays or isolated are a common feature of historic villages and towns in Southern Europe. The encyclopedia contains four examples, from Greece, Italy, Slovenia and Portugal. Although the typologies presented are rather different, the constructional details and material used show very little variation, at least in the first three cases.

The Italian example shows an array of buildings from an historic hilltop town centre (WHE Report 28). They have common party walls and variable number of stories on the hillside (up to 2 or 3) and valley side (usually 4 or 5, with a maximum of 6). The typical house is usually formed by one or two masonry cells, depending on the depth of the block, with a staircase running, usually but not necessarily, along the party walls. The masonry is made of roughly squared stone blocks set in lime mortar, and the walls are made of two leaves with a rubble core at the base, tapering at the upper floors. Limestone is used for the blocks, while a particular type of tuffa stone is used for the lintels above openings. At ground level there are sometimes vaulted structures, while the upper stories were originally spanned by timber beams, with joist and timber boards covered by tiles. The roof structure is usually original and made of timber trusses. In recent past, many of the original floors have been replaced either with iron "I" beams and jack arches (refurbishments occurred before the World War II) or more recently with weakly reinforced concrete slabs (last fifty years). Other alterations include vertical extensions, closing and opening of windows, introduction of hygienic services. A high proportion of these houses show traditional iron ties introduced in the 18th Century to tie together orthogonal walls and floors, to ensure better seismic performance. After the introduction of modern seismic codes in 1980s many buildings have undergone further strengthening, represented by RC ring beams and concrete jacketing of walls.The example chosen, in Nocera Umbra, was hit by an earthquake in 1997 of magnitude 5.6. Typical damage ranged from out of plane failure and corner damage for buildings with no strengthening to shear cracks and in plane failure in buildings with ties and stiff diaphragm.

Similar damage patterns were reported also for buildings hit by the 1999 Athens earthquake (WHE Report 16). This earthquake came as a surprise, since no seismic activity was recorded in this region for the last 200 years. According to strong-motion recordings, the range of significant frequencies is approximately 1.5-10 Hz, while the range of the horizontal peak ground acceleration were between 0.04 to 0.36g. The most heavily damaged areas lie within a 15 km radius from the epicenter. The consequences of the earthquake were significant: 143 people died and more than 700 were injured. The structural damage was also significant, since 2,700 buildings were destroyed or were damaged beyond the repair and another 35,000 buildings experienced repairable damage. According to the EERI Reconnaissance report (EERI 1999), in the meizoseismal area, most stone masonry structures with undressed stones, constructed in the first half of the century, suffered significant damage. This included partial collapse of external walls, collapse of corners, separation of the two walls converging at a corner, and extensive cracking.

Figure 1: a) Typical array of Buildings in Nocera Umbra; b) corner failure in a building with stiff roof diaphragm (Greece) ; c) shear cracks on a wall with ties and stiffened vaulted floors (Nocera Umbra); d) introduction of concrete ring beam at each storey level (Nocera Umbra).

Historically, perhaps the most exemplar case of systematic strengthening of stone masonry buildings was carried out in Portugal, after the 1755 destructive earthquake of Lisbon. As the fire that ensued destroyed almost entirely the medieval downtown, this was rebuilt following new urban planning criteria including a number of mandatory seismic resilient features (WHE Report 92). The buildings, called 'Pombalino' from 'Marquês de Pombal', the king's minister responsible for the reconstruction, can be identified by the existence of a three-dimensional timber structure named 'gaiola pombalina' enclosed in internal masonry walls above the first floor. This timber structure is like a cage made of vertical and horizontal elements braced with diagonals and clad in brickwork. Exterior walls like facades and party walls between buildings are single leaf masonry. Roofs are built with timber trusses and ceramic tiles and floors have timber joists structures covered with timber boards. Ground floor walls are roughly dressed stone masonry supporting a system of vaults made of clay tiles, with stone arches. Foundations are made of short and small diameter timber piles connected by a timber grid. Indeed, the inclusion of the timber braced structure would allow for possible partial collapse of the external masonry walls, with no frame, while at the same time preventing the collapse of the internal structure and hence reducing the number of deaths in case of a future earthquake. The buildings original use was commercial at the ground floor and residential at the upper floors, with a housing unit or two per storey. For the buildings that maintain their original conception, the main problems result from poor maintenance like loss of waterproofing for roofs, leading to water ingress in the walls, particularly critical for timber structural elements. Most buildings were adapted to new functions in the past century, leading to the opening of larger shop windows at ground floor, sometimes accompanied by complete demolition of the exterior masonry walls at this level. Other important changes are interior walls demolition at any floor, introduction of stairs and elevators and the addition of more storeys. The expected collapse mechanisms due to earthquake actions are overturning of facades (out-of-plane) or shear failure at the plane of the walls at ground floor level (global shear mechanism), leading to a global collapse mechanism. The introduction of a concrete/steel beam around the entire perimeter of the building, at roof eaves level, is a typical reinforcement solution to connect roof to walls, avoiding out-of-plane mechanism of facades. The introduction of steel elements/pre-stressed cables or anchors connecting parallel masonry walls increases strength connection of masonry walls, especially at corners. Steel elements are also used to connect detached timber elements from floors and 'gaiola' to masonry. New techniques applying new materials like fibre Reinforced Polymers (FRP), for example, are also used to increase the capacity of connections of timber elements that compose the 'gaiola'.

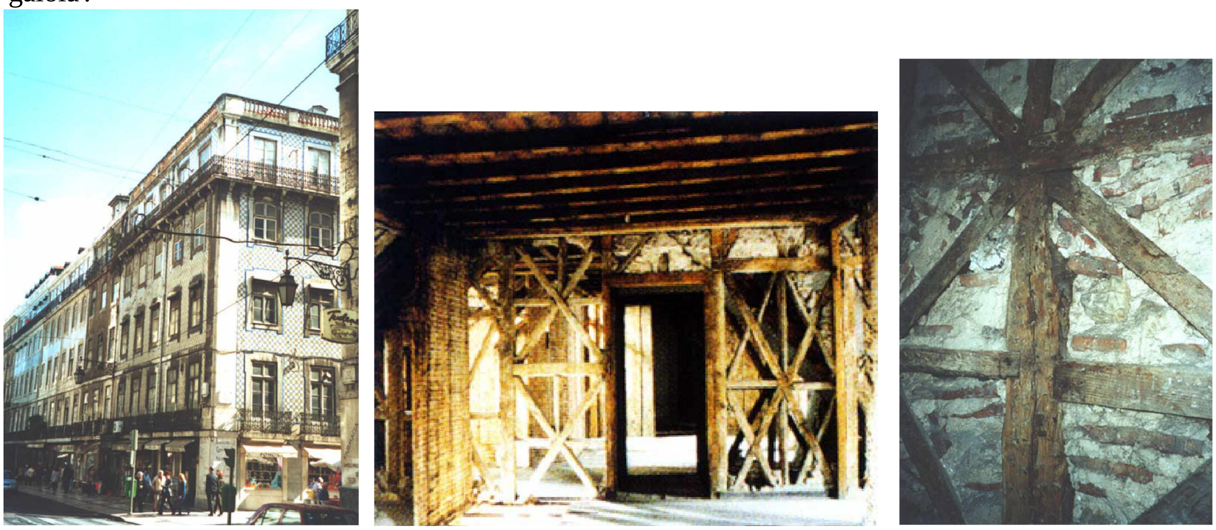


Figure 2: a) typical building block In the Baixa pombalina, Lisbon, Portugal; b) the cajola; c) cajola with infilled masonry

A more modern example of extensive retrofit of stone masonry residential houses is represented by the Slovenian experience (WHE Report 58). Rubble stone masonry detached houses were the common residential housing type throughout northwestern Slovenia. After their destruction during World War I, these houses were rebuilt, mostly with the recycled stone material (from the buildings that were demolished). Many houses of this type were subsequently damaged during the last two earthquakes in Slovenia (1976 Friuli and 1998 Bovec). In order to preserve the country's architectural heritage, about 66% of these houses were strengthened after the earthquakes. The epicenters of the main shock on May 6, 1976 (M= 6.5 , focal depth 20-30 km) and the strongest aftershock on September 15, 1976 (M=5.9) were in Friuli, Italy, 20.5 km from the border between Italy and Slovenia. In Italy 965 people died and enormous damage was caused. In Slovenia, the maximum intensity was VIII EMS. Out of 6,175 damaged buildings, 1,709 had to be demolished and 4,467 were retrofitted (Ladava 1982). The strongest earthquake with the epicenter in Slovenia in the 20th century occurred on April 12, 1998. The epicenter was approx. 6.3 km South-East from the town of Bovec, and the focal depth was between 15 and 18 km. No building collapses were reported, however out of 952 inspected buildings, 337 were found to be unsafe, out of which 123 beyond repair. The effectiveness of strengthening methods applied in 1976 was analyzed. A seismic deficiency common to this house type is the lack of connecting stones between the two exterior and interior wythes of which the wall are made and the large number of voids in the rubble infill. This is usually remedied by systematic filling of the voids with injected cementitious grout. The grout is injected into the wall through injection tubes and nozzles, which are built into the joints between the stones uniformly over the entire surface of the wall. Low pressure is used to inject the grout. The injected grout has the purpose to bond the loose parts of the wall together into a solid structure. When orthogonal walls are not tied together, then steel ties are placed symmetrically at each floor level on both sides of all bearing walls, just below the floor structures, in horizontal notches, which have been cut in the plaster up to the wall surface. Ties are threaded at the ends and bolted on steel anchor plates. Ties are usually of diameter 16 - 20 mm. Another common seismic flow is the fact that the floor structures are supported only by the interior wall wythe and are not attached to the external wythe. In this case steel elements are used to anchor the timber joist or in some case replacement concrete floor slab to exterior wall surface.

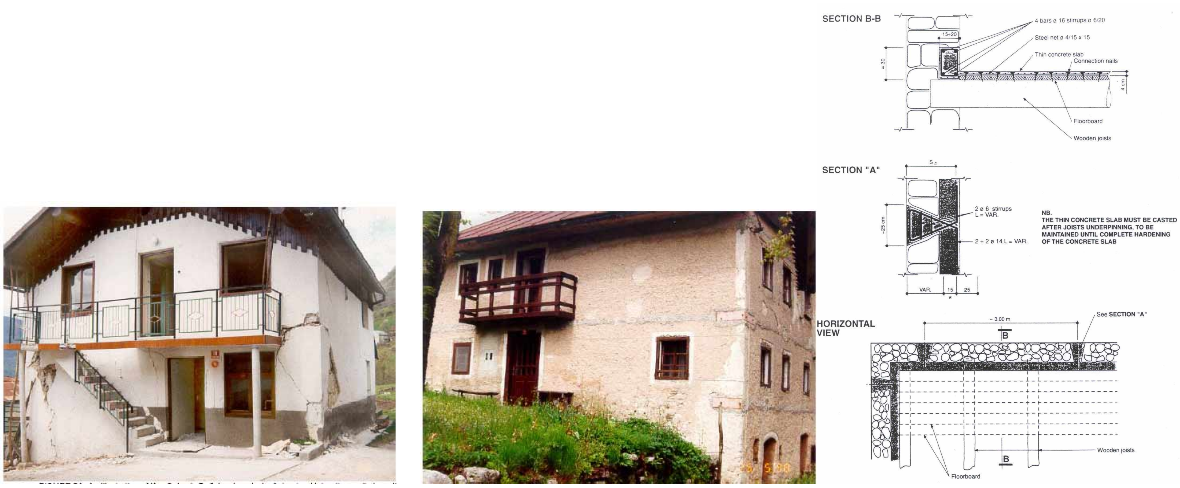


Figure 3: a) typical damage to a rubble masonry building in Slovenia; b) implementation of retrofitting measures; c) detail of strengthening of existing timber floor with thin r.c. slab, r.c. ring beam and r.c. dove tail anchorages.

BRICKWORK MASONRY BUILDINGS

For this construction material, there is a substantial variation of architectural and structural typologies. In the following 3 different cases from Italy, Romania, and Slovenia are reviewed.

Historic Brickwork Masonry Buildings

This single-family housing type is found throughout Central Italy, and has a typology very similar to the one seen in the previous section, except for the use of brickwork rather than roughly dressed stone (WHE Report 29). Typically, a house is 3-story high and built in arrays. The main facade of the house faces a narrow road. The ground floor level, often with vaulted structure, partially built in the rock, is used for storage, while the other two storeys are used for residential purpose. Typical buildings of this type are approximately 3 m wide and 9 m long. Building height on the front side is on the order of 4.5 m, whereas the height on the rear side is larger (close to 5 m). All the walls are made of unreinforced brick masonry in lime mortar, with typical brick dimensions of 160x60x320 mm. In the case of very old masonry the depth of brick units can reach 80 mm. The lime mortar joints are 3-5 mm thick. The floor structures besides the ground floor, are made of timber joist and tiles spanning from the façade wall to an internal timber beam. Some buildings have an internal spine wall. The roof is made of timber and it is double pitched, sloping down towards the front and rear walls. Buildings of this type are expected to demonstrate rather good seismic performance, mostly due to their modest height, but also to the good quality of the fabric. In most cases they are historically retrofitted with ties connecting front and rear wall. Typical seismic deficiency are the presence of slender internal wall, and some time the poor connection of façade to party walls. In this case, the façade is vulnerable to out of plane failure and this would also cause collapse of the floor structures.

Typical strengthening techniques widely applied include:

- installation of new RC ring beam at the roof level. It is very important to achieve a good level of connection between the new RC ring beam and the existing masonry, if further seismic damage is to be avoided.
- installation of metallic ties. It is very important to accomplish a regular distribution of ties - irregular tie distribution may be a cause of earthquake damage.
- Shotcreting- strengthening walls with shotcrete jackets. The strengthening consists of installing new steel wire mesh and attaching it to the existing wall with through-wall ties or strips spaced at 500 mm on centre both horizontally and vertically. The limitation of this intervention is the fact that it needs to have proper foundation if it is to be effective. Also it severely limits the "breathing" of the wall and this may produce severe decay of both bricks and lime mortar.
- Stitching and grouting - consists of drilling holes through the walls and installing steel bars; subsequently, the holes are grouted with cement grout. For historic buildings it is essential that the grout is lime based and the bars are stainless steel or other non corroding material.

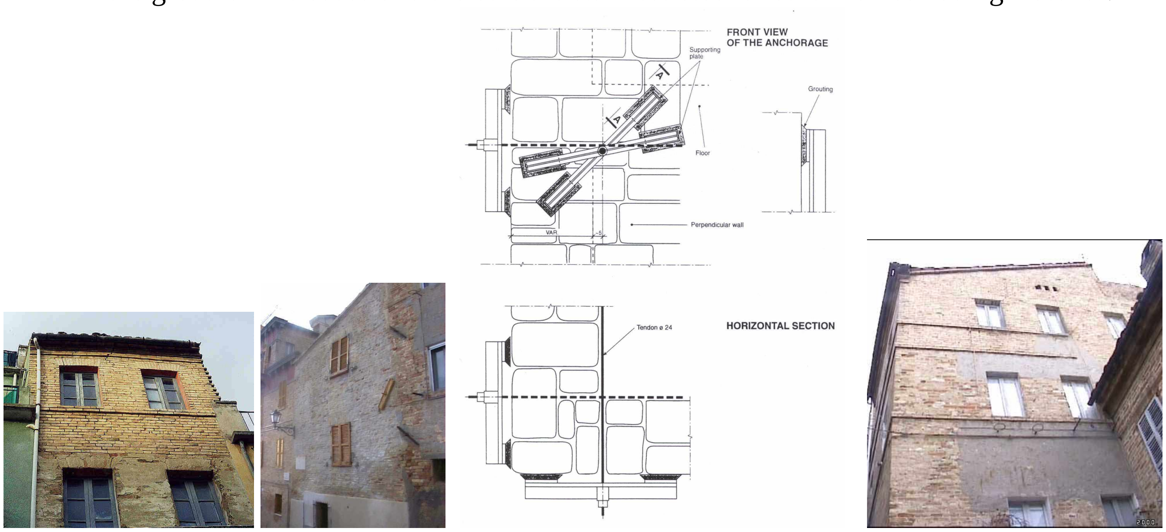


Figure 4 a) typical building; b) modern ties insertion; c tie anchorage constructional detail; d) grouting to improve capacity of spandrel walls.

Figure 5: Wagon house; a) Typical damage; b) Retrofit with "ties" for "wagon" type house

The Romanian "Wagon House" (~1850-1940)

This is one of the oldest types of housing in Romania (WHE Report 85). It is common especially in towns from the southern part of the country. The houses have been designed as semidetached, but constructed individually. The single housing unit has rectangular elongated plan shape, with enhanced entrance on the long side. The load bearing system consists of two longitudinal unconfined brick masonry walls and several transversal confined brick walls, separating the rooms which form a wagon like array, hence the name of this building type: “wagon-house”. The horizontal structural system is made of wood boards and joists. They performed well except of occurrence of rifts and cracks (Figure 5). Anchoring the walls or floors of adjacent units by means of metal ties is a typical strengthening method (figure 5). Sometimes the original floors, either of timber or jack arches on iron beams were replaced with reinforced concrete slabs, while the provision of vertical concrete posts or r.c. frames around doorways are also common.

Isolated brick masonry house (Romania ~1900-1940)

This type of urban housing was constructed in Romania in the 1930s as single-family housing for the middle class (WHE Report 84). A great variety of buildings exist of this structural type. The one described in this report has load-bearing brick masonry walls constructed of mud mortar. The floor structure consists of timber planks and joists (Figure 6). The most common type of damage was in the form of cracks and falling chimneys. Four mid-rise masonry residential buildings and one hotel (~75 housing units) collapsed in the 1977 earthquake in Romania. The most common reinforcement method applied for Romanian brickwork is jacketing of walls, practiced since the 1940s. Additionally to techniques developed after the 1977 earthquake, new retrofit techniques have been developed in recent years, such as the use of polymer nets in mortar, although its long-term effects to the durability of the masonry have not yet been sufficiently researched. For smaller cracks, either injection of cement grouts, or, in case of historically relevant buildings, special lime based grouts, have been used. Further, conceptual design errors have been corrected through replacement of heavy walls with lightweight ones.

Unreinforced brick masonry apartment building (Slovenia)

This construction was commonly used for residential buildings in all Slovenian towns, and it constitutes up to 30% of the entire housing stock in Slovenia (WHE Report 73). The majority of buildings of this type were built between 1920 and 1965. Buildings of this type are generally medium-rise, usually 4 to 6 stories high. The walls are of unreinforced brick masonry construction laid in lime/cement mortar. In some cases, the wall density in the longitudinal direction is significantly smaller than the transverse direction. In pre-1950 construction, there are mainly wooden floor structures without RC tie-beams. In post-1950s construction, there are concrete floors with RC bond-beams provided in the structural walls. Roof structures are either made of wood (pitched roofs) or reinforced concrete (flat roofs). Since this construction was widely practiced prior to the development of the seismic code (the first such code was issued in 1964), many buildings of this type exceed the allowable number of stories permitted by the current seismic code (maximum 2 or 3 stories for unreinforced masonry construction). Buildings of this type have been exposed to earthquake effects in Slovenia, however the most significant damage to this construction type was reported in the 1963 Skopje, Macedonia earthquake, in which many buildings of this type were severely damaged or collapsed, due to the predominant ground motion occurring in the weak direction of the building. The buildings of this type are characterized by two longitudinal exterior walls with the majority of openings located in these walls, and two exterior walls in the transverse direction with a few smaller window openings or no openings at all. The average area of a window opening is 1.8 m.sq. in longitudinal exterior bearing walls. The exterior walls in the transverse direction are characterized with smaller kitchen or toilet window openings of typical area less than 0.5 m.sq. The area of balcony door and window openings is approx. 4.0 m.sq. The door area in the exterior and interior loadbearing walls is approximately 2.0 m.sq. The total area of openings is approximately equal to 30 % of the longitudinal exterior wall surface area. The whole area of Slovenia has been divided into the two "seismic insurance zones". The residential buildings are divided into two categories depending on the age of construction: older buildings, built before or in 1965, and the newer buildings, built in 1966 or later. For the higher seismic zone, the annual insurance rate is 0.105 % of the building value for older buildings and 0.07 % for the newer buildings. For the lower seismic zone, the annual insurance rate is 0.07 % and 0.045 % of the building value for older and newer buildings respectively.

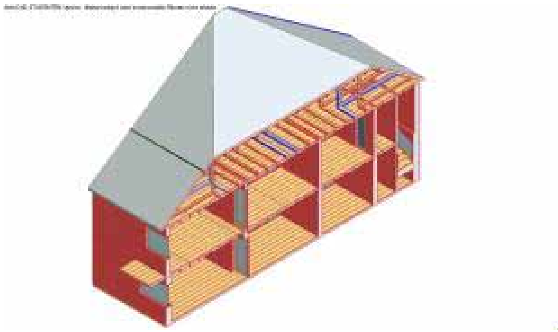


Figure 6: Key load bearing elements (Romania) **Figure 7: Typical unreinforced brickwork (Slovenia)**

REINFORCED CONCRETE BUILDINGS

There are 10 different entries in the database for concrete structural types in Europe. In the present review, the entries for Romania and Turkey are considered. This is due to two orders of reasons. On one hand, by analyzing the Romanian entries it is possible to identify the entire development of the modern urban apartment building block, and how both its form and its structure has evolved to accommodate varying economic conditions and seismic preoccupations. On the other hand we are all aware of the disastrous performance of substandard concrete residential buildings, built in the last 20 to 30 years in conditions of seismic deregulation or modest seismic regulation enforcement. Although damage of this typology has been widespread in Europe as well as in other continents, nowhere like in Turkey the death toll caused by it has been tremendous. Finally an alternative form of reinforced concrete construction type is presented, which has shown good performance both during the Izmit-Duzce and the Bingol earthquakes, although its occurrence is very modest.

Performance of reinforced concrete buildings in Romania

The earthquake prone area of Romania is affected by damaging earthquakes (M>7.0) with the epicenter in Vrancea three times a century. Most of the buildings described are located in Bucharest, the capital with 2 millions inhabitants, which lies 150km south of the seismogenetic zone, in the main direction of propagation of the waves, on non-homogenous alluvial soil deposits, strongly increasing the vulnerability. Depending on the age of construction these buildings have been affected by up to four strong earthquakes (1940, 1977, 1986 and 1990), of which two were damaging (1940, 1977). The 1977 event killed 1,578 people including 1,424 (90%) in Bucharest and injured 11,221 (7,598 in Bucharest) (Lungu et al. 2000).

Buildings of the Romanian "Avantgarde" (~1920-1940)

This urban housing construction was practiced in Romania 1907-1945 but mainly in the late 30's. These buildings are mid or high-rise, often with two basements. For purely residential buildings a high basement is common. There are several functional variations of this type combining flats, offices and shops on the whole building type. Purely residential buildings (WHE report 96) and buildings with commercial ground floor are discussed (WHE Report 97). Many of these buildings are corner buildings and more vulnerable. The number of housing is variable. While in smaller mid-rise buildings there can be as few as one or two large luxury flat each floor (figure 8), for higher buildings up to eight small one-room flats, sometimes without kitchen (figure 9), are common. The shape is irregular both in plan and in elevation. Upper floors may have recesses from the façade. The load bearing structure is a RC frame designed for gravitational loads only. At least the façade has walls with solid clay brick masonry infill. Purely residential buildings have thin 6cm thick flexible RC slabs, for larger spans there was an alternative solution of 20cm thick slabs with hollow bricks. Of the 31 buildings which collapsed in 1977, 21 were blocks of flats and 2 office buildings (633 housing units). Purely residential and commercial ground floor buildings were heavily damaged in approximately equal proportion. Besides collapse of the masonry infill, the RC frame suffered mainly column damage. Many of the retrofit provisions for this type of building regard repairs. Damaged RC columns were repaired locally, and so were damaged RC beams. Superficially damaged RC beams were repaired through plating with woven glass embedded in epoxy resins. Slightly damaged masonry walls were repaired with cement mortar injections. Strengthening measures, carried out as preparedness measures, are column jacketing and beam jacketing with RC jacket, or steel profiles fixed with epoxy resins. Adding of structural walls is becoming increasingly common.

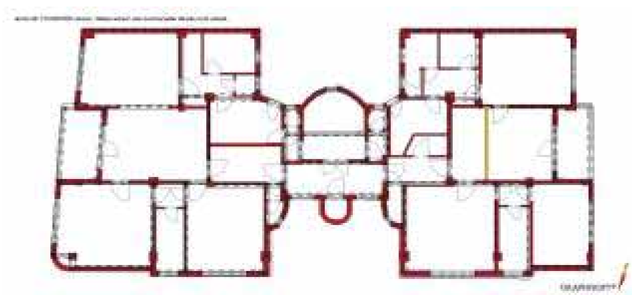


Figure 8: Architectural plan of a current floor

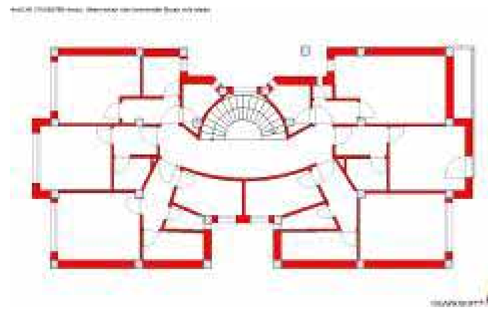


Figure 9: Architectural plan of a current floor

Buildings of the post-war time (~1940-1950)

This is a Post-World War II variant of the previous building type (WHE Report 71). It was practiced in Romania until the nationalization in 1947. Buildings of this type are usually 7 to 11 stories high and the main load bearing structure consists of a reinforced concrete space frame with reinforced concrete diagonal bracings (Figure 10a). The floor structure consists of RC solid slabs and beams cast in place. The frames are infilled with brick masonry walls. These buildings were designed according to the temporary guidelines issued in 1941 after the damaging earthquake of 1940, based on German guidelines like the circular from 1925 being in use before. Buildings of this construction type have experienced sever damage, in the columns, infill walls and at the diagonal-column-beam node, however, collapse was not reported. After the 1977 earthquake brick walls were replaced by lightweight ones, diagonals removed and columns jacketed (Figure 10c).

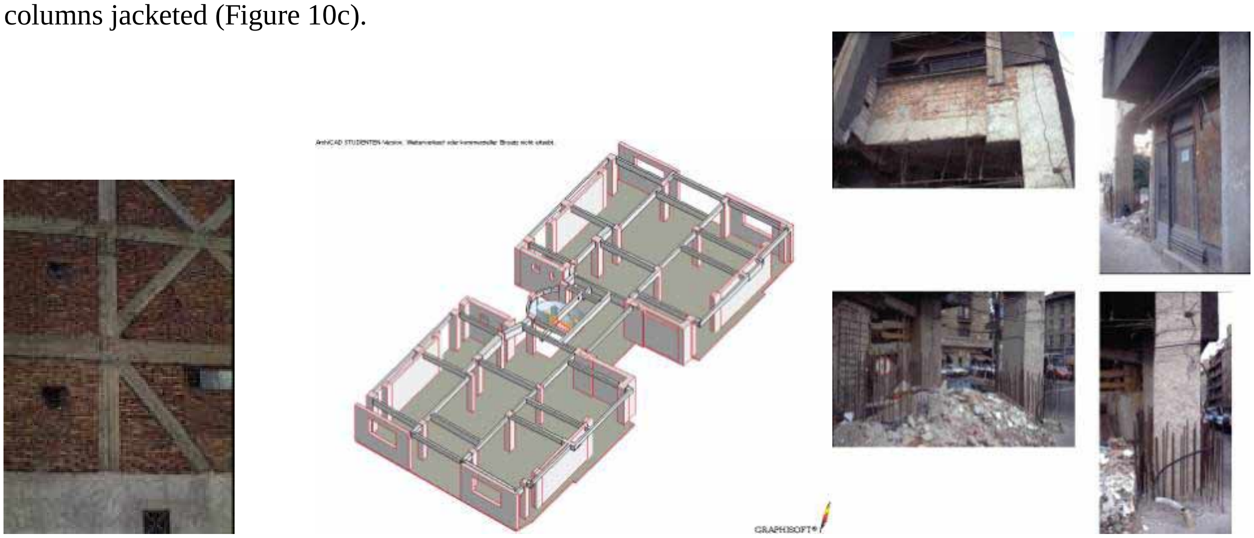


Figure 10: a) Critical structural detail: RC diagonals; b) Retrofit through combined methods: addition of structural walls and column jacketing in early RC frame buildings (Report 96 c) Retrofit with column jacketing on early RC frame buildings in today's practice (Report 97)

Buildings of the "International Style" (~1960-1977)

This is a typical urban multi-family housing unit practiced throughout Romania in the period from 1965 to 1989 (WHE Report 78). Concrete structural wall construction was commonly used for the residential construction and it accounts for over 60% of new housing. Buildings of this type are typically 11 stories high. The walls are continuous throughout the building height and laid in two directions at the perimeter of rooms in the so-called "fagure" plan shape. The code of reference was the 1963 Romanian Building Code, updated in 1970. The 1963 code assumed intensity 7 for the Bucharest area.

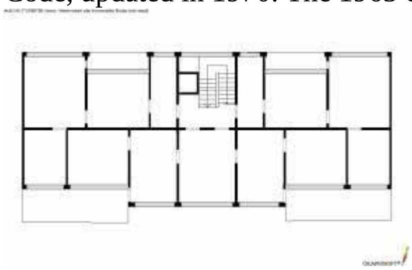


Figure 11: Key seismic deficiency: significantly smaller wall density in the longitudinal direction

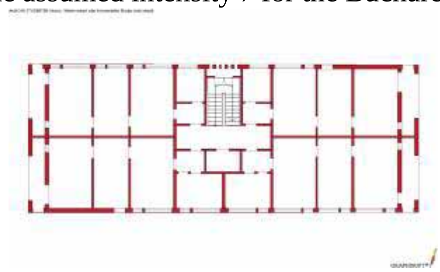


Figure 12: Key seismic feature: Layout of bearing walls in a current floor

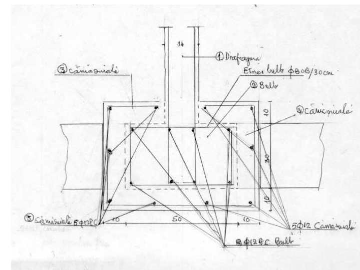


Figure 13 Retrofit of boundary elements for "OD" type house (Report 78)

One example of building of this type has only one centrally located longitudinal wall, while the transversal walls have columns attached at the ends (type OD, Figure 11). The "OD" type suffered damage of various extent in the 1977 earthquake, and one building unit totally collapsed (in total two structural wall residential buildings with 77 units and one structural wall office building collapsed in the earthquake). Buildings with their longitudinal direction aligned to the direction of seismic waves propagation (NNE-SSV) were most affected. Characteristic retrofit works concerned the jacketing of the end columns. Another building typology (type Y, Figure 12) is characterized by three load bearing walls in the longitudinal direction, which improves significantly its seismic capacity. These buildings behaved rather well, the only damages observed being cracks and rifts.

Post-modern buildings of the socialist time (~1977-1990)

This multi-family urban housing construction appeared in Bucarest in the late 1960s and became fairly common between 1997 and the early 1990s. The load bearing system is a precast reinforced concrete large panel construction. Such buildings are typically high-rises (10 to 11 storeys), although there are also low to medium rise buildings (4 to 8 storeys) of this construction type, with different structural details. They consist of a rectangular plan, housing four apartments per floor. The panels are mechanically coupled at the base with continuous vertical reinforcement bars. The lateral stability is provided by columns tied to the wall panels. The special feature of the building described in this report is not having prefabricated façade elements, but lightweight block masonry. Boundary elements are used instead of the columns as stiffening elements at the exterior. There was no significant damage reported to the buildings of this construction type in the 1977 earthquake. Consequently, this construction technique continued to be practiced afterwards. The building described in this report was built after 1977 and so far has not been exposed to damaging earthquakes.

Figure 13: Typical photo

Performance of reinforced concrete buildings in Turkey

Background

Turkey is located in a seismically active region and has experienced many major earthquakes. The major earthquakes of the last decade caused extensive damage and huge economic loss. Table 1 summarizes casualties and losses due to recent earthquakes in the country. The high tolls are clear indications of the fragility of the housing stock in Turkey against earthquake effects. There are numerous reasons discussed in detail in WHE for the high vulnerability of the building stock.

Table 1. Earthquake Losses in Turkey: 1992-1999

Earthquake (Date,dd.mm.yy)	Lives Lost	Housing Units Damaged	Housing Units Collapsed or Razed	Number of Persons Left Homeless	Estimated Total Economic Loss, in $B
Erzincan (13.3.1992)	645	8000	1450	8000	0.75
Dinar (1.10.1995)	100	6500	2043	-	0.25
Adana-Ceyhan (28.6.1998)	150	21,000	2000	24,000	0.5
Kocaeli (17.8.1999)	>18000	320,000	26 000	600,000	>20
Düzce (12.11.1999)	812	10,100	800	-	1

Reinforced Concrete Frame Buildings

The severe urban earthquakes of last decade in Turkey caused substantial damage to reinforced concrete frame buildings in the cities of Erzincan, Dinar, Adana, Ceyhan, Yalova, Gölcük, İzmit, Adapazarı and Düzce (WHE Report 64). The observed damage patterns in these regions were generally similar and mostly resulted from substandard construction practice and noncompliance to the seismic design codes. Out of nearly 1400 buildings damaged in Dinar, 37% were heavily damaged, 21 % experienced moderate damage and 42% were assigned light damage. The information contained in Table 2 reveals both the prevalence and high vulnerability of reinforced concrete buildings in Dinar.

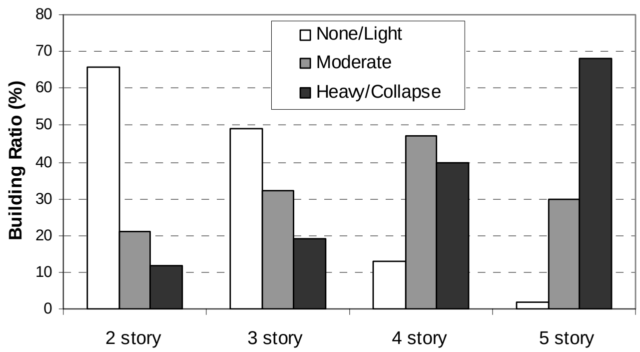
Table 2. Classification of 201 Collapsed Buildings in Dinar (Wasti and Sucuoglu, 1999)

Structural System	Number of Stories	Number of Collapsed Buildings	
		Single Story Collapse	Total Collapse
R/C Frame	≥4	33	28
R/C Frame	3	29	18
Brick Masonry	4	32	41
Brick Masonry	3	10	4
Composite Masonry	2	6	-

The two devastating earthquakes of 1999 led to widespread damage in many cities (more than 200 000 buildings were damaged) including Adapazarı, Düzce, Yalova, Gölcük and İzmit (Ural, 1999). Table 3 presents damage distribution in the cities strongly affected from the earthquakes. In Gölcük and Degirmendere, 16 % of a total of 2746 buildings were rated as collapsed or heavily damaged. Of the total damaged buildings, 1953 were reinforced concrete (19% classified as heavily damaged or collapsed) and the remaining were masonry type (4% rated as heavily damaged or collapsed) (AIJ, 1999). The higher vulnerability of reinforced concrete frame buildings is clearly emphasized by these damage rates. A comprehensive survey of reinforced concrete buildings with number of stories higher than 3 in Adapazarı revealed that 21 % of nearly 2100 damaged buildings investigated were classified as heavily damaged or collapsed (Gulkan et al. 2003). Figure 14 shows the damage distribution of 6478 2-5 storey reinforced concrete buildings in Düzce after the 1999 earthquakes (Sucuoglu and Yilmaz, 2001). The noteworthy increase in damage with the number of stories is common and is an indication of substandard construction practice.

Table 3. Damage Distribution after 1999 Earthquakes (Ural, 1999)

Name of Region	Collopsed (%)	Heavily Damaged (%)	Other (%)
Adapazarı	32.5	48.7	18.8
İzmit	38.6	35.1	26.3
Yalova	44.2	43.4	12.4
Avcılar	19.4	66.7	13.9
Değirmendere	37.2	47.6	14.2
Gölcük	50.0	32.9	17.1
Total	38.6	44.4	17.0



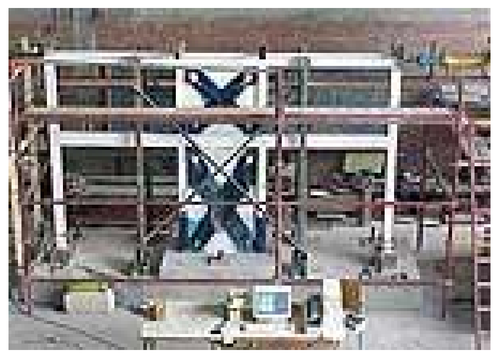


Figure 14. Damage Distribution in Düzce; Figure 15. Strengthening of Infill walls with CFRP (METU tests)

Observations after the recent earthquakes revealing high levels of vulnerability for reinforced concrete frame buildings prompted homeowners and government institutions to repair/retrofit damaged buildings as well as to assess the expected performance of existing buildings in earthquake prone areas and strengthen them if necessary. The retrofit or strengthening techniques used in Turkey for RC frame buildings is almost unique and confined to addition of in-fill reinforced concrete walls. Although a substantial number of buildings have been rehabilitated and retrofitted after the earthquakes only a few of them have been subjected to earthquakes. Several retrofitted reinforced concrete buildings in Erzincan were observed to have performed satisfactorily after 1992 Erzincan earthquake. On the other hand, these techniques have been tested by exhaustive experimental work and proven to be efficient. In an effort to seek more economical and practical strengthening techniques, recent research have focused on using carbon fiber reinforced polymers (CFRP) to reinforce the masonry infill wall elements that are enclosed by RC frames (Figure 15). The objective is to strengthen reinforced concrete frame buildings that have infill walls with minimal distraction to the occupants. Although complete guidelines for field implementations have not developed yet, research results are quite promising (Erdem, 2003).

Tunnel Form Buildings

The second construction type included in WHE is tunnel form building type that has been used in Turkey since the late 1970s and early 1980s as a rapidly constructed, multi-unit residential form (WHE Report 101). The structural system of this construction type is composed of reinforced concrete walls and slabs that are cast in a single operation by using steel forms having accurate dimensions. So no beams and columns exist in the building (Figure 16a). The lateral and gravity loads are transferred uniformly to the mat foundation. The nonstructural components such as facade walls, stairs and partition walls are prefabricated elements that are connected to the main structure. In the current Turkish Seismic Code (Turkish, 1997), this construction type is not handled separately thus the specifications for reinforced concrete walls are used in the design. In the code, the specified minimum reinforcement ratio for shear walls is 0.0025, which can be reduced to 0.0015 if the density of walls satisfies certain criteria that suits tunnel form buildings. A typical reinforcement detail for walls of a typical tunnel form building designed according to the Turkish Seismic Code (Turkish, 1997) is shown in Figure 16b.

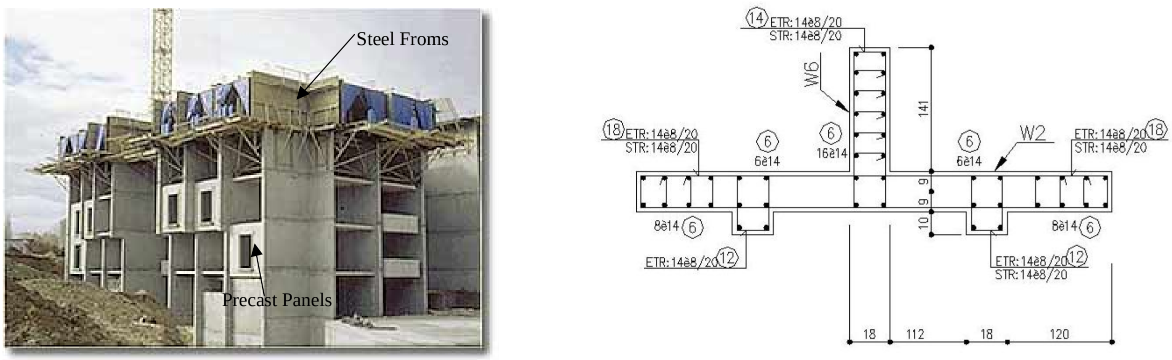


Figure 16. a) A Tunnel Form Building under construction, b) Reinforcement detailing of walls in a typical Tunnel Form Building

The earthquake resistance of this construction type has been superior thus it has been increasingly utilized also as permanent housing in post-earthquake reconstruction programs. The monolithic casting of walls and slabs provides high seismic performance and results in horizontal and vertical continuity. The buildings of this type were subjected to the two major earthquakes of 1999 and the earthquake of 2003 (May 1st, 2003 Bingöl earthquake) and no cases of significant damage were reported. The only points of weakness for these buildings have been pre-cast panels and stairs, which are not considered as structural components. Due to their outstanding performance, no rehabilitation or retrofit techniques are implemented for this construction type in the country.

Building Stock in Istanbul

There is extensive research supporting that Istanbul is on the verge of being struck by a destructive earthquake. Substantial endeavor has been used for predicting the likely damage and loss in the city against several scenario earthquakes. The content of building stock in Istanbul consisting of approximately 800 000 buildings (according to the building census data of 2000) is displayed in Figure 16 and Table 4 along with the expected fault rupture geometry corresponding to a magnitude 7.4 (Mw) earthquake. The high percentage of reinforced concrete frame buildings cautions the officials that high losses are anticipated. It should also be noted that many buildings were examined and assessed for their seismic capacity and only a small portion of them have been rehabilitated.

Table 4. Building Inventory in Istanbul based on the 2000 Building Census Data (Japan, 2002)

Structural form	**RC (%)**	**Tunnel Form (%)**	**Steel (%)**	**Wood (%)**	**Masonry (%)**	**Prefabricated (%)**
Percentage population	74.4	0.1	0.1	1.5	28.8	0.1

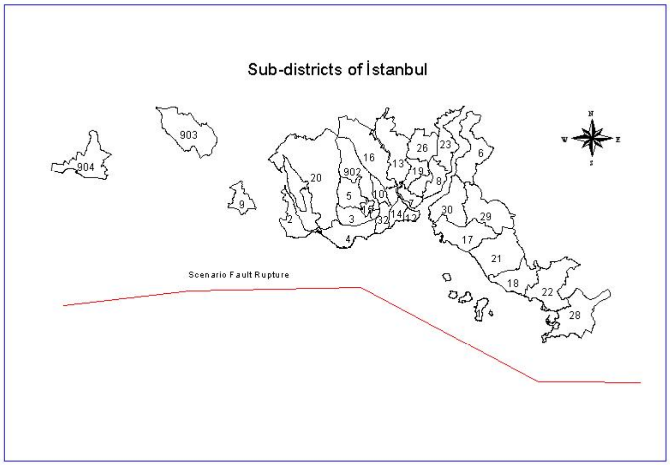


Figure 17. Expected Fault Rupture and Districts in Istanbul

CONCLUSIONS

The paper clearly outlines the common features across Europe both of the traditional and the more recent building stock. Common building techniques and materials lead to similar level of seismic vulnerability and specific constructional problems.

Table 5: Comparison of vulnerability levels of the analyzed typologies

Typology	**Vulnerability class (according to EMS ’98)**				
	A	**B**	**C**	**D**	**E**
#15 RC frame Greece					X
#16 Stone masonry Greece	X				
#28 Stone masonry Italy		X			
#29 Brickwork Italy		X			
#58 Stone masonry Slovenia	X				
#64 RC frame Turkey		X			
#71 RC frame Romania				X	
#73 Brickwork Slovenia			X		
# 78 RC Shearwall Romania					X
#84 Brickwork Romania			X		
#85 Stone masonry Romania		X			
#92 Pombalino frame Portugal			X		
#96 RC frame resid. Romania			X		
#97 RC frame comm. Romania			X		
# 101 Tunnel form Turkey				X	

One way of measuring the relative performance of the structural types discussed here is to check to which vulnerability class they have been assigned. This decision, in most cases based on observed performance, is reached in agreement between the authors of the form, their reviewers and the editorial panel and serves as synthetic guidance to users of the database. In the table above only the central value assigned tp the vulnerability is recorded, and this can be slightly misleading because does not take into account best and worse performance related to quality construction and structural detailing. However, considering the level of representation of the various building types within European urban areas, the table draws a clear picture of the average level of vulnerability and hence of expected risk throughout Europe.

One of the real strength of the WHE is the possibility to compare performances over a much wider range of events and specific variations of buildings types. Most importantly the WHE represents a unique databank of upgrading and strengthening strategies, providing first hand information on the success of their implementation. One part of the database that has not been revised in this paper is the information related to the economic and policy-making aspects of seismic risk, as related to specific residential typologies. This information, together with the technical data discussed above, provides a unique and easily accessible source of expert knowledge not just to the seismic engineering community, but also to the other professions involved in seismic risk reduction efforts and to the public at large. This project is only possible because of the volunteer effort of all participants. Their contribution is gratefully acknowledged. A complete list of all contributors can be found on the website. Special thanks to EERI; IAEE, John Martin and Associates and Adobe for supporting the project.

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