DAMAGE TO REINFORCED CONCRETE BUILDINGS DUE TO THE AEGION, (GR) 1995 EARTHQUAKE

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Key words: reinforced concrete buildings, damage, vulnerability, earthquakes

Abstract: *The damage observed in reinforced concrete buildings due to the Aegion, Greece, 1995 Earthquake is examined in connection to several structural characteristics such as the height of the building, the location within the building block, the type of the ground storey and the date of construction, since different seismic codes were in force over different time periods. The building sample includes all the r.c. buildings of the town while the damage is graded on the basis of in-situ observations conducted by the engineers of the Sector for Earthquake Rehabilitation. The main conclusion deemed is that the period of construction is of great importance, as even buildings deemed to be most vulnerable suffered light or no damage, if they were designed and constructed according to recent seismic codes.*

1. INTRODUCTION

The seismic performance of the building stock in an area depends on the dynamic characteristics of the individual buildings, on their regularity in plan and in elevation, and on the period of construction as different seismic design codes applied over the long period during which the building stock has developed. In this study the seismic performance of r.c. buildings due to the Aegion earthquake that struck the town of Aegion, in Greece is examined.

Aegion is a typical small town of the Southern Greece with 20,000 inhabitants. Its building stock consists on one hand of one- to two-storey masonry buildings erected from the second half of the 19th century until recently, and on the other hand of reinforced concrete buildings erected after Word War II until the present time, according to the specifications of three different national seismic codes. On June 15, 1995 an earthquake of M_s=6.1 shoock Aegion. The damage in the epicentral area was severe. There were 26 casualties due to the collapse of two multi-story reinforced concrete buildings.

This paper is based on a project on the seismic vulnerability of Aegion funded by the Greek Earthquake Planning and Protection Organization, after the 1995 earthquake, Fardis *et al* [1]. Herein the seismic response of the reinforced concrete buildings of the town is studied in correlation with characteristics such as the age, the type of the ground storey (open or fully infilled with masonry walls), the number of storeys, etc., considered likely to affect their vulnerability. Damage was significant over a wide area. Nonetheless the study is restricted in the central and older part of the town presented in Fig. 1, because it is only in that area that all types of buildings could be found. The area included 1157 r.c. buildings as well as 857 buildings of structural masonry.

A common characteristic of the reinforced concrete buildings in Greece is that the structural frame the floors and the roof alike are made of in-situ reinforced concrete and are infilled with masonry of hollow clay bricks. Although masonry infills are considered non structural, they are constructed of masonry units that qualify for structural masonry as well. As such, they have a low void ratio (about 35%) and produce infills that are stiff and strong. Another typical characteristic of residential buildings in Greece is their strong irregularity in plan.

The data collected after the earthquake in-situ comprise: the exact location of the building, the time of construction, the number of storeys, the type of ground floor (without or with infills, i.e "pilotis" or not), as well as the characterisation of the damage degree according to the teams of the Sector for Earthquake Rehabilitation (SER). Additional data collected from the files of SER concern the cost and the method of repair of the buildings in the study area, but as the entire repair process was slow the data collected during the study period are limited.

A similar study on the behaviour of masonry buildings has been conducted by Karantoni and Bouckovalas[3] for the town of Pyrgos and by Karantoni [4] for Kalamata, Aegion and Patras.

2. SEISMIC DAMAGE OF REINFORCED CONCRETE BUILDINGS

The 1157 reinforced concrete buildings of Fig. 1 represent 57% of the building stock of the study area. The remaining 43% consists of masonry buildings (the grey ones in Fig. 1). A large number of the r.c. buildings (37.5%) were built between 1955-1965 and have up to two storeys (55.7% of the total). Only 103 buildings (8.8% of the total) have 5-8 storeys and are generally new buildings.

In Greece teams of engineers characterise the damage of the buildings immediately after the earthquake, for the purposes of immediate occupancy or threat to occupants and others. They use the well-known system of three colours. The "green" tag is given to undamaged buildings and to those with slight structural or non structural damage appropriate for the immediate occupancy. The "yellow" tag is given to moderately damaged buildings that will ultimately have to be repaired and are not safe for immediate occupancy during the after shock period. The "red" tag is used for severely damaged buildings that need to be evacuated until a repair and strengthening design is done and implemented. "Red" buildings may be demolished if they are not economic to repair. According to this characterization 77.5% of the r.c building were tagged as "green", 20% as "yellow" and 2.5% as "red" (see Fig. 1), whereas one multi-story building collapsed in the study area.

In the next paragraphs, some characteristics of the reinforced concrete buildings that may influence their seismic performance are examined. These characteristics are the location in the building block, the number of storeys, the period of the construction, that relates to the use of different seismic codes and the type of the ground floor (open, i.e. "pilotis" or fully infilled). Damage is related to each one of these characteristics as well as to the combination of these factors.

Figure 1: Grade of damage of r.c buildings in Aegion according to SER

3. DAMAGE IN RELATION TO THE PERIOD OF CONSTRUCTION

The Aegion earthquake shoock a Greek town for the first time after the application of the 1984 revision of the 1959 Greek Aseismic Code. This revision introduced for the first time seismic detailing of concrete members (dense stirrups at the ends of beams and columns, boundary elements in walls, etc.) as well as capacity-design of frames (of members in shear and of the frame for the strong column-weak beam rule), without a change in the base shear coefficient that applied since 1959 and gives the opportunity for the very first time to study the effect of these rules to the vulnerability of reinforced concrete buildings. So, in order to examine this factor, the buildings grouped in three age groups, a) the "*old buildings*" group (17% of the r.c. buildings), namely the buildings built before 1959, that is before any seismic code is in use, and were older than 35 years old when the earthquake struck the town, b) the "*intermediate age buildings*" group (74% of the r.c buildings) consists the buildings were 35-11 years old at the same time period and were studied and built according to the specifications of the 1959 Seismic Code, and c) the "*recent buildings*" group includes the remaining 9% of the buildings which studied and built according to the 1984 revision of the Greek Seismic Code. The later were of an age less than 10 years the day of the earthquake and their design and especially the construction were affected from the knowledge on the seismic performance came by Kalamata earthquake, 1986, Fardis *et al* [2].

Table 1 presents the correlation between the age of the buildings and the grade of damage according to SER. From this table is obvious that the percentage of damaged buildings decreases as the period of construction is newer, namely the buildings are designed according to the specifications of recent seismic codes that have considered the results of the researches related with this subject. It is important that not a single building built after 1984 was "red" tagged although the ground floor of 46.7% of these buildings was of the "pilotis" type that are more vulnerable to seismic actions. The "red" tagged buildings are 50% older than the "green" ones, as one can see in Table 2. This result encourages the research on the improvement of the seismic behaviour and endures the introduction of restrictions on the construction and of detailing on reinforcement as well as the usefulness of often revisions of design codes based on the progress of the relevant research and the seismic performance of buildings after an earthquake that is real scale experiment.

Characterization	Recent	Intermediate age buildings	Old buildings	Total
Green	92,5%	75,7%	62,3%	77,5%
Yellow	7,5%	21,9%	28,3%	20%
Red	0,0%	2,4%	9,4%	2,5%

Table1: Damage characterization in relation to the period of construction

Characterization	Mean age (years)
Green	22
Yellow	27,5
Red	33

Table 2: Relation of mean age and damage of the reinforced concrete buildings

4. DAMAGE IN RELATION TO THE LOCATION IN THE BUILDING BLOCK

In the older part of Greek cities and towns, buildings are built in contact, without a seismic or other joint separating them. It is commonly considered that such buildings at the corners of the building block are more vulnerable than intermediate ones, owing to: a) double asymmetry of infill walls in plan (the two sides in contact with the adjacent buildings are fully infilled, while all openings are concentrated at the two other sides), b) possibility of pounding with the adjacent buildings and the resulting outward accumulation of inelastic storey drifts (i.e. towards the street), c) the lateral support of the few most vulnerable intermediate buildings by the adjacent stronger ones, and the luck of such support on both sides of corner buildings. As is seen in Table 3, “yellow” and “red” buildings at the corner of the building block are more than intermediate ones. This difference is not conclusive that there is very strong influence of the location in the building block on vulnerability. This conclusion is the same, even when each building group is examined separately according to the age.

Characterization	Location in the building block		Total
	Corner	Intermediate	
Green	73,2%	79,2%	77,5%
Yellow	24%	18,3%	20%
Red	2,8%	2,5%	2,5%
Total	100%	100%	100%

Table 3: Relation of the damage and location in the building block

5. DAMAGE IN RELATION TO THE NUMBER OF STOREYS

Higher structures are commonly considered to be more vulnerable to earthquakes. In this Section, the influence of the number of storeys on vulnerability is investigated. The buildings were classified into three groups, depending on the number of storeys: a) the low-rise buildings with 1-2 storeys (644 buildings, or 55.7% of the sample), b) the middle-rise buildings with 3-4 storeys (409 buildings, or 35.4%) and c) the higher-rise buildings with 5-8 storeys (103 buildings, or 8.9%). The buildings of the group c) are generally newer, the average number of storeys of buildings less than 10 years old is 3.5 storeys while on average the old buildings have 1.75 storeys. This is the result of the changes in building codes, in the technology of construction and in preferences of owners and designers over the years.

Table 4 presents the relation between the number of storeys and damage. It is obvious that although the higher-rise buildings are newer and usually built according to the 1984 provisions of the seismic code, they were damaged more than low-rise ones. The “green” tagged higher-rise (5-8 storeys) buildings are much less than the low-rise ones. This observation support the conventional wisdom that damage increases with building height.

	Number of storeys			
Characterization	1-2	3-4	5-8	total
Green	82,6%	72,9%	62,1%	77,5%
Yellow	15,1%	24,5%	33%	20%
Red	2,3%	2,6%	3,9%	2,5%

Table 4: Relation of damage and number of storeys

6. RELATION OF THE DAMAGE AND THE TYPE OF GROUND FLOOR

The distribution of stiffness with the elevation in the structure affects seismic performance. The heightwise variation of the stiffness of the structural system is sufficiently taken into account in the analysis of the buildings according to modern seismic codes. Nonetheless, as masonry infills are considered as no structural, any change in their strength and stiffness from storey to storey escapes from the analysis, regardless of how abrupt and drastic such a change might be. Such an abrupt change often takes place at the ground floor as at the ground storey infill walls maybe reduced to form large open shopping areas or for parking ("pilotis" type of building). In Table 5 and Fig. 2 as "regular" are termed those buildings without such abrupt changes of infills in elevation. Because "regular" buildings were slightly more vulnerable than those of the "pilotis" type, Table 5 relates with the damage not only the type of ground storey but also the period of construction. These data and Fig. 2 suggest that "new" buildings according to Section 3, namely the buildings designed after the 1984 seismic code revision, overall did not develop but only light damage. Especially, not a single such building was tagged as "red", although a large percentage of them were of the "pilotis" type. The percentage of "intermediate age" buildings that developed severe damage is the same (2.4%), irrespective of the type of ground storey. "Old" buildings built without any seismic code were in general low-rise and although the buildings of the "pilotis" type represents a little percentage of them, those severely damaged were almost twice as much as the "regular" ones. The results from Table 5 are interesting in view of the observations after the Kalamata 1986 earthquake (with $M_s = 6.0$) where practically all buildings of the "pilotis" type developed some damage.

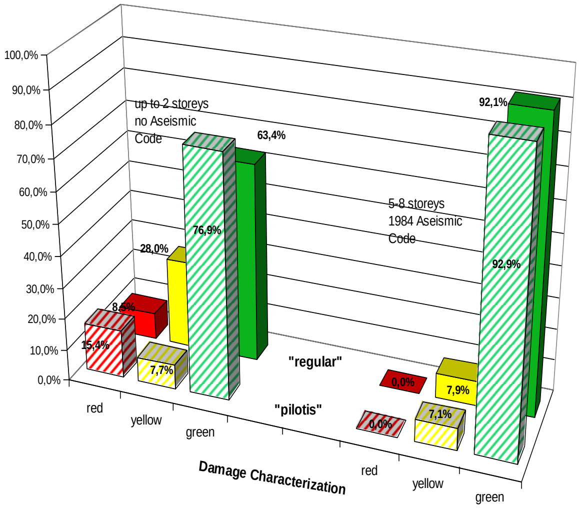

Figure 2: Grade of damage of "old" low-rise buildings and "new" higher-rise ones in relation to the type of ground floor

Type of ground storey	Recent buildings (according to 1984 Code)			Intermediate age buildings (according to 1959 Code)			Older buildings (no Seismic Code)		
	green	yellow	red	green	yellow	red	green	yellow	red
Pilotis	90,4%	9,6%	0%	76,4%	21,2%	2,4%	76,9%	7,7%	15,4%
Regular	94,4%	5,6%	0%	75,5%	22,1%	2,4%	60,2%	31,2%	8,6%
total	92,5%	7,5%	0%	75,7%	21,9%	2,4%	62,3%	28,3%	9,4%

Table 5: Relation of damage, design code and type of ground storey

7. RELATION OF DAMAGE WITH PERIOD OF CONSTRUCTION, NUMBER OF STOREYS AND TYPE OF GROUND STOREY

In this Section all factors affecting the vulnerability of r.c. buildings are correlated. Table 6 presents the damage of the buildings in correlation with the number of storeys, the type of ground storey and the seismic code applying at the time of construction. It is obvious from this Table that the period of construction, namely the code in force, is the main factor that affects the vulnerability of reinforced concrete buildings. Fig. 2 points out that even the less vulnerable low-rise buildings are much more vulnerable than higher-rise ones, if they are built without any seismic code.

No of storeys	Design code	Damage	Number of buildings	
			Type of ground storey	
			Normal	Pilotis
Up to 2 storeys	1984 Code	red	0	0
		yellow	0	0
		green	29	20
	1959 Code	red	5	1
		yellow	61	12
		green	322	95
	No Code for earthquake resistance	red	7	2
		yellow	23	1
		green	52	10
3-4 storeys	1984 Code	red	0	0
		yellow	5	3
		green	58	39
	1959 Code	red	7	3
		yellow	64	21
		green	138	58
	No Code for earthquake resistance	red	1	0
		yellow	6	0
		green	4	0
5-8 storeys	1984 Code	red	0	0
		yellow	5	3
		green	58	39
	1959 Code	red	7	3
		yellow	64	21
		green	138	58
	No Code for earthquake resistance	red	1	0
		yellow	6	0
		green	4	0

Table 6. Damage of r.c. buildings in relation to design code, type of ground storey and number of storeys

The former are even more vulnerable, if they are of the “pilotis” type. On the contrary, not a single higher-rise building, even of the “pilotis” type developed severe damage. This highlights the importance of enforcement of modern design codes that promote the local and global ductility of concrete buildings.

8. CONCLUSIONS

As concluded from the data collected in-situ about the characteristics supposed to affect the seismic performance of reinforced concrete buildings and the damage of the structural system, as graded by the Sector for Earthquake Rehabilitation: a) the location in the building block, (corner vs intermediate buildings) affects only slightly the vulnerability, b) the damage increases with the number of storeys of the building, c) infills or not of the ground floor is not important to the structures built with older seismic codes, but of little importance for those designed according to relatively modern ones, d) the period of construction, namely the seismic code in force for the design seems to be of at most great importance. As a result, the older buildings practically not designed for earthquake resistance, are more vulnerable and measures for their seismic retrofit are urgently needed in order to minimize damage in future earthquakes.

It is noteworthy that, although the buildings that had been designed with the 1984 revision of the Greek Seismic Code fared much better than the older ones, the shock from the damage and casualties due to Aegion earthquake, as well as from a smaller event that shook the Grevena – Kozani area in northern Greece one month earlier, were sufficient to trigger immediate and exclusive enforcement of the new concrete and seismic design codes, that were in parallel use with the 1984 revision for several years. As those codes were radically different from the older ones (they introduced for the first time modal response spectrum analysis, as well as ultimate strength design, etc.) they had not been enforced until then, due to resistance from practising engineers. The 1995 codes were moderately revised in 2000 to conform better to the ENV version of the Eurocodes. They were also applied with the drastic increase in the acceleration values in the seismic zonation map. It is this set of codes, ensuring a much higher level of seismic safety than the 1984 revision of the seismic code that will remain in force until the introduction of the EN-Eurocodes to European Union countries in the second half of this decade.

Acknowledgment
The Greek Earthquake Planning and Protection Organization funded this study.

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