DOI: 10.23968/2500-0055-2020-5-4-03-17

THE 30TH OF OCTOBER SAMOS-GREECE EARTHQUAKE. ISSUES RELEVANT TO THE PROTECTION FROM STRUCTURAL DAMAGE CAUSED BY STRONG EARTHQUAKE GROUND MOTIONS

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Abstract

Introduction: This is a report of issues relevant to the protection from structural damage that is sustained by various types of structures when subjected to strong earthquake ground motions. **Purpose of the study:** This study became relevant due to the recent intense earthquake activity to the Greek island of Samos which left its impact on numerous structures of various types. **Results and discussion:** Initially, a summary is presented discussing the effort that has been made in Greece trying to confront with the consequences of this extreme loading condition to the built environment. Next, a summary report is given for certain types of structures which suffered the most. They include old Christian Greek Orthodox churches as well as other buildings on conservation status. The sustained damage is discussed together with a brief numerical study that tries to simulate numerically the observed behavior. Finally, a brief discussion with relevant conclusions are presented as a result of the observed damage combined with similar observations and studies made during the last decades.

Keywords

Earthquake structural damage, Christian churches, Cultural heritage, Samos island, Unreinforced masonry structures, Reinforced concrete structures, Numerical simulations.

Introduction

An earthquake occurred 16km North from the Greek island of Samos on the 30th of October 2020 (11:51GMT) with a magnitude of M6.7 (Figure 1). This island is located at the East side of the Aegean Sea an area seismically active (Ambraseys et.al., 1996; Ambraseys and Simpson, 1996; Papazachos, 1990). The main event caused widespread structural damage mainly at numerous low-rise old unreinforced masonry buildings of this island. It also caused heavy damage and collapse of multi-story reinforced concrete (R/C) buildings at the city of Izmir located at the coastline of mainland Turkey towards the North-East, approximately 60km from the epicenter of this earthquake. This study focuses on the effects of this seismic strong motion on the Greek island of Samos. The Institute of Engineering Seismology and Earthquake Engineering (ITSAK) operates a strong motion accelerograph at the city of Vathi, the capital of Samos. The ground accelerations at Vathi due to the main shock were recorded by this instrument (see preliminary report of ITSAK (Preliminary report, October 2020) and ETAM (Preliminary report, November 2020) having peak horizontal ground acceleration 227cm/sec^2 and peak vertical ground acceleration 134cm/sec^2. The main event was followed by a considerable number of aftershocks, with the aftershock sequence being active for sometime. (Figure 2).

Figure 1. Map indicating the epicenter of the 30th of October 2020 seismic event

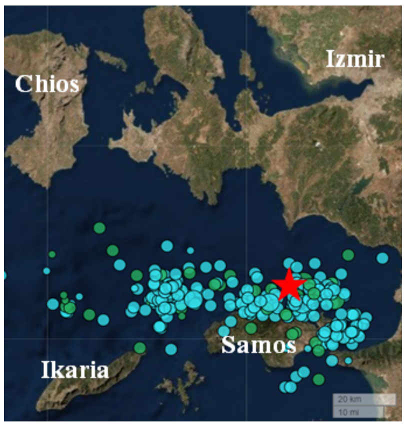

Figure 2. The epicenter of the 30th of October 2020 main event and the following aftershock sequence

Figure 3. Map of the North coast-line of the island of Samos where the two main cities of Vathi and Karlovasi are located

The most spectacular structural damage could be observed at the two main cities in the island, its capital (Vathi) and Karlovaisi 25km to the West (Figure 3). Due to the location of the epicenter, having the same epicentral distance from both Vathi and Karlovasi, and due to the generating mechanism of this earthquake that followed an almost East-West fault line, as can be seen from the aftershock sequence, it can be reasonably assumed that the strong motion characteristics at Karlovasi would be quite similar to those of the recorded strong motion at Vathi. This assumption will be made use of in the section presenting selected numerical analyses predictions of the structural response of damaged buildings.

A few minutes after the main shock the waterfront of Vathi was subjected to a tsunami which, despite its relatively small height, flooded the shops located at the waterfront causing considerable damage to its contents (Figure 4). Moreover, a permanent uplift of approximately 20cm was noticed at the embankment of the waterfront after the end of the current earthquake sequence (Figure 5). Apart, from the structural damage at the two main cities of Vathi and Karlovasi, widespread damage was also observed for unreinforced masonry structures located at many villages of this island. Despite the fact that this earthquake was also felt at the neighbouring Greek islands of Ikaria and Chios no structural damage was reported there.

Main issues towards protection from structural damage

During the last fifty years various parts of Greece have been subjected to a number of damaging earthquakes ranging from Ms=5.2 to Ms=7.2 on the Richter scale (Manos, 2011). Some of these earthquakes, not necessarily the most intense, occurred near urban areas and thus subjected various types of structures to significant earthquake forces leading to damage. Manos (Manos, 2011), lists information relevant to these events and discusses the observed structural damage as well as the effort that was made in Greece towards increasing the

Samos Earthquake 30-10-2020, Damage from the main event at the city of Vathi, capital of the island of Samos. The interior of the shops at the water front was damaged by a tsunami that followed a few minutes after the main shock

Figure 4. Indication of the tsunami at the waterfront of Vathi

Samos Earthquake 30-10-2020. There were signs of 20cm land rise at the water front.

Figure 5. Permanent uplift of the embankment at the waterfront of Vathi

DOI: 10.23968/2500-0055-2020-5-4-03-17

earthquake protection and reducing the seismic risk. The main conclusions are also listed here.

1. Classification of structural damage and their underlying causes: *Improve effective measures to contain damage* (Organization of Earthquake Planning and Protection of Greece (OASP), 2001).

2. Repair and strengthening of damaged structures*: Improve the means of such interventions by establishing relevant code provisions as well as by introducing effective methods and techniques* (Organization of Earthquake Planning and Protection of Greece (OASP), 2001).

3. Upgrade the seismic design: *Revise the Seismic Code provisions* (Paz, 1994; EAK-2000 Greek seismic Code; Provisions of Greek Seismic Code with revisions of seismic zonation, 2003; ELOT EN 1998-1/2005-05-12).

4. Plans for earthquake preparedness: *Assimilate past experience and provide for effective future plans and actions.*

5. Assessing the vulnerability of certain type of structures (schools, hospitals, public buildings etc.): *Introduce measures for upgrading their seismic resistance* (Organization of Earthquake Planning and Protection of Greece (OASP), 2001).

6. Education specialized in earthquake engineering: *Introduce specialized studies in Universities. Establish special courses for the retraining of Engineers.*

7. The enrichment of the strong motion data base: *Expand the national network. Introduce specialized networks with modern instruments in dams and bridges.*

8. *Address the problem of old structures built without seismic design provisions which include structures of cultural heritage to be preserved.*

A discussion of the above issues will be the main objective of the present studies using the recent experience from the structural damage observations caused already by the recent earthquake at Kefalonia island (Manos and Kozikopoulos, 2015) and the current Samos island earthquake sequence (Preliminary report, November 2020) as stimulus for this purpose. As a starting point of this discussion the following facts must be listed:

a. Referring to ***point 1 above,*** the classification of structural damage and its underlying causes for structures built in Greece with reinforced concrete (RC) is being well understood, utilizing the observations selected during the earthquake activity of the last 40 years. Manos (Manos, 2011), tried to summarize some of the most outstanding cases which are also listed here.

b. Referring to ***point 2 above***, design provisions has been published as a legal documents for assessing the vulnerability of existing RC structures as well as for designing the necessary interventions towards upgrading their resistance for future earthquakes (Organization of Earthquake Planning and Protection of Greece (OASP), 2001). Moreover, similar provisions have been currently published in draft form to be valid for existing masonry structures. Moreover, the Greek Organization of Earthquake Planning and Protection (OASP) has supported financially numerous research projects which focused on confronting with the earthquake vulnerability of existing structures. The same objective had the financial support of funds provided by the European Union. The actual effect of all this research will be discussed further.

c. Referring to ***point 3 above***, apart from issuing a New Greek Earthquake Resistant Design Code since 1995 (EAK-2000 Greek seismic Code; Provisions of Greek Seismic Code with revisions of seismic zonation, 2003) the relevant seismic design provisions of the Euro-Code (Euro-Code-8, ELOT EN 1998-1/2005-05-12) have become active and are applied as design provisions for all structures that are built in Greece since 1995. Apart, from particular design provisions included in these codes, which are in accordance with current knowledge in Earthquake Engineering and Earthquake Resistant Design, they also include provisions relevant to defining the design spectra as well as new seismic zoning. This represents a considerable upgrading in resisting the effects of strong earthquake ground motions. Figure 6 depicts the current new seismic zoning map of Greece together with the corresponding horizontal design ground acceleration levels. The island of Kefalonia belongs to Zone III whereas the island of Samos belongs to Zone II with horizontal design ground acceleration equal to 0.36g and 0.24g, respectively (g the acceleration of gravity).

d. Referring to ***point 4 above,*** the Greek Organization of Earthquake Planning and Protection (OASP, https://www.oasp.gr/en) has assimilated past damage experience and has being active in distributing relevant publications in schools

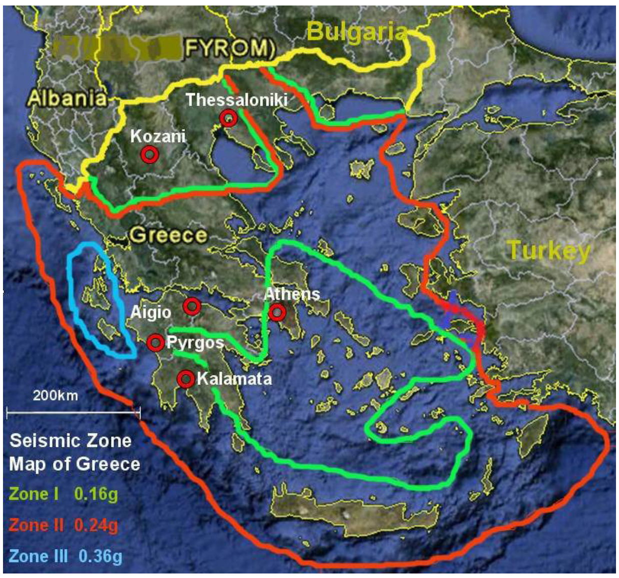

Figure 6. The seismic zoning map of Greece

and universities. Moreover, this organization has upgraded all the actions relevant to earthquake emergencies. This was shown to be effective both in the recent earthquake events of both Kefalonia and Samos islands.

e. Referring to ***point 5 above,*** an upgrading was established in the design and construction of structures for these particular structures (schools, hospitals, public buildings etc) which were built since 1995, when the provisions of the new seismic code of Greece were enforced, till today (EAK-2000 Greek seismic Code; Provisions of Greek Seismic Code with revisions of seismic zonation, 2003). However, the upgrading of existing structures that fulfill these functions and were built prior to 1995 is progressing with low pace (Organization of Earthquake Planning and Protection of Greece (OASP), 2001; Paz, 1994).

f. Referring to ***point 6 above***, a large effort has been accomplished in seminars for professional engineers on issues referring to the seismic behaviour of structures and on upgrading their seismic resistance. Moreover, a large number of postgraduate one-year courses are running for the last 20 years in all the departments of Civil Engineering of the major Greek universities focusing on all aspects of earthquake resistant design of new and existing structures.

g. Referring to ***point 7 above***, the existing National Network of strong motion accelerographs was enriched with numerous new instruments and covers the whole of Greece. During the last 20 years these recordings have been stored on a data base that is managed by the Institute of Earthquake Engineering and Engineering Seismology (ITSAK see (Preliminary report, November 2020)). The resent Samos earthquake ground motion was recorded by such instrument. Moreover, certain important structures, e.g. the large cable stayed bridge at Evripos-Halkis, have been also permanently instrumented.

h. The seismic vulnerability of old structures constructed before the enforcement of earthquake resistant design in Greece (1958) represents one of the most difficult problems (Manos, 2011). This is evident after a strong earthquake event in Greece with this type of structures being severely damaged in many localities. This is covered in many past publications. One category of structures with a heavy toll is old Christian Orthodox churches (Manos and Kozikopoulos, 2015; Manos, Soulis, Karamitsios, 2012; Manos and Karamitsios, 2013; Manos, 2016; Manos, Kotoulas and Kozikopoulos, 2019; Manos and Kotoulas, 2019). Another type of vulnerable buildings are those with particular architectural features which were declared to be under conservation; this means that the owners should abide with a particular legislative framework dictating the rules of any works to be done in such a structure (Manos and Papanaoum, 2009). This issue is partly discussed here taking advantage of the stimulus given by the recent "Samos" earthquake. The two main cities of the island of Samos, e.g. Vathi, the capital of the island, and Karlovasi, included such old buildings which sustained structural damage as will be shown in the following. Moreover, old churches were also heavily damaged. Similar damage was also widespread in the surrounding villages. In what follows, typical damage of this type will be presented and discussed. It must be underlined here that relatively modern structures built with a degree of seismic resistant design, despite the intensity of the ground motion, are reported as not developing any structural damage, with a few exceptions. On the contrary, in the nearby city of Izmir in Turkey a large number of RC multi-story residential buildings collapsed with a heavy death toll (Figure 7). Although the report for these collapsed buildings is pending it should be underlined that the Turkish seismic design code and the construction practices in Turkey have been upgraded well after the upgrading that was enforced in Greece in 1995 together with the Euro-Codes (ELOT EN 1998-1/2005-05-12; EN 1996-1-1:2005) sometime afterwards. It is believed, that the enforcement of the provisions of the "New Seismic Code of Greece" (EAK-2000 Greek seismic Code; Provisions of Greek Seismic Code with revisions of seismic zonation, 2003) together with the Euro-Codes has reduced substantially the seismic

Figure 7. One of the many collapsed multistory buildings at Izmir-Turkey

vulnerability of the structures designed and built in Greece according to these provisions after 1995.

Earthquake performance of multi-story reinforced concrete buildings in Samos

As already mentioned, in contrast to the collapsed multi-story buildings at Izmir-Turkey (Figure 7), fortunately very few reinforced concrete buildings in Samos Island sustained structural damage. Figure 8 depicts such a case of damaged columns at the ground floor of a RC multi story building. This particular structural deficiency of a “relatively” flexible ground floor for RC multi-story buildings in Greece has been identified for some-time (see Manos, 2011) This is due to the fact that the shear force demands at this level are amplified because of the increased stiffness of the upper floors, which is not accounted for in design that ignores the influence of well-built masonry infill in these upper floors. Moreover, the old design provisions did not focus on shear reinforcing detailing of these ground floor columns to provide for sufficient shear strength to meet such shear amplified demands.

Unfortunately, this structural deficiency which leads to such high-risk structural damage for the safety of RC multi-story buildings is systematic and is present in numerous RC multi-story buildings designed and constructed in Greece prior to the enforcements of the provisions of the New Seismic Code of Greece in 1995, as was shown by the earthquake damage observations of Kalamata 1986, Pyrgos 1993, Kozani and Aigio 1995 and Athens 1999 (see Manos, 2011). Another particular structural deficiency is the “accidental” formation of short columns in RC framed structures again by building strong infill in various openings. These two structural deficiencies have been identified from past earthquake observations to be the main contributing factors of high-risk performances of RC multi-story structures in Greece which may seriously jeopardize the safety of multi-story structures in many Greek cities. It is fortunate that, as is shown at the right part of figure 8, temporary wooden supports were added in the case of this building in Samos in order to ascertain, up to a degree, its structural stability during the aftershock earthquake sequence in Samos. This was shown to be critical in many post-earthquake observations (see Manos, 2011).

Observed structural damage at the Greek island of Samos

As already mentioned, the reinforced concrete building in Samos designed even with the old seismic code provisions did not sustain serious structural damage, with a few exceptions. The damage to be reported here focuses on old structures. Severe structural damage was sustained by numerous Christian Greek Orthodox churches (Manos and Kozikopoulos, 2015; Manos, Soulis, Karamitsios, 2012; Manos and Karamitsios, 2013; Manos, 2016; Manos, Kotoulas and Kozikopoulos, 2019; Manos and Kotoulas, 2019).

The most spectacular structural damage of this type occurred at the church of Koimiseos Tis Theotokou in Karlovasi-Samos. This church is depicted in figure 9 prior to this earthquake. It is a three-nave cruciform “Basilica” with a central dome, built in 1898, and it serves as the Cathedral for the city of Karlovasi. According to information, as yet unverified, this church was subjected to at least two strong earthquake ground motions (1904 and 1954). It has a considerable height in order to accommodate the women’ quarter as a second story at the West part of the church. The central

Figure 8. Shear failure of columns at the ground floor “soft” story of RC multi-story buildings at Samos island (ETAM report Nov. 2020 (Preliminary report, November 2020))

semi-spherical dome is supported by a cylindrical tympanum with numerous windows which remained undamaged. The central nave extends longitudinally in the East-West direction from the central dome by semi-cylindrical domes covered by a wooden roof with tiles and at their two East and West ends by ¼ spherical parts. Similarly, the transept extends in the North-South transverse direction from the central dome with semi-cylindrical domes covered by a wooden roof with tiles and at their two North and South ends by ¼ spherical parts. Internally, the three naves are supported by colonnades formed by a series of slender columns rising from the floor to the level of the base of the central spherical dome and the adjacent semi-cylindrical domes. The following observations can be made from the structural damage observed at this church, depicted in figures 9, 10, 11, 14 and 15.

1. The structural system of the church of Agiou Konstantinou kai Elenis at Kozani (Figure 11) is similar to the one depicted here. This church was studied extensively by Manos (1997) and Soulis and Manos (2019) in order to understand the mechanisms that generated the structural damage it sustained during the 1995 earthquake sequence and propose a retrofitting scheme that was constructed in order to strengthen its earthquake resistance (Manos et.al., 1997; Soulis and Manos, 2019; Manos, Soulis, Diagouma, 2008). It was shown from this investigation that large seismic forces are generated by the considerable masses of the spherical and cylindrical domes that form the superstructure and the combination of relevant eigen-modes excited by the characteristics of the horizontal components of the seismic ground motion. These seismic forces are generated at considerable height and are resisted mainly by the peripheral stiff unreinforced masonry walls whereas the internal colonnades provide minimal resistance to these horizontal seismic forces due to their relative flexibility.

2. The seismic resistance of these walls is reduced by the openings (doors or windows) as well as by the way they are constructed in terms of materials and construction techniques. Figures 9 and 10 indicate that these are constructed with unreinforced masonry. An extensive research of the structural damage of unreinforced masonry peripheral walls forming numerous churches at the Greek island of Kefalonia is described in summary form in references (Manos and Kozikopoulos, 2015; Manos, Kotoulas and Kozikopoulos, 2019; Manos and Kotoulas, 2019). This investigation combined the results of 3-D numerical simulations and assumed failure criteria to demonstrate the validity of utilizing realistic limit-state scenarios in order to explain successfully the observed damage. These limit-state scenarios include mainly shear or diagonal in-plane modes of failure or out-of-plane bending modes of failure. Such typical damage is depicted in figure 15.

3. The partial collapse of the superstructure must be attributed to such combined in-plane and out-of-plane modes of failure of the peripheral walls. This partial collapse causes the loss of support for

Figure 9. The church of Koimiseos Tis Theotokou (Assumption of Virgin Mary) in Karlovasi the Cathedral church of Samos, prior to the 30th of October 2020 earthquake

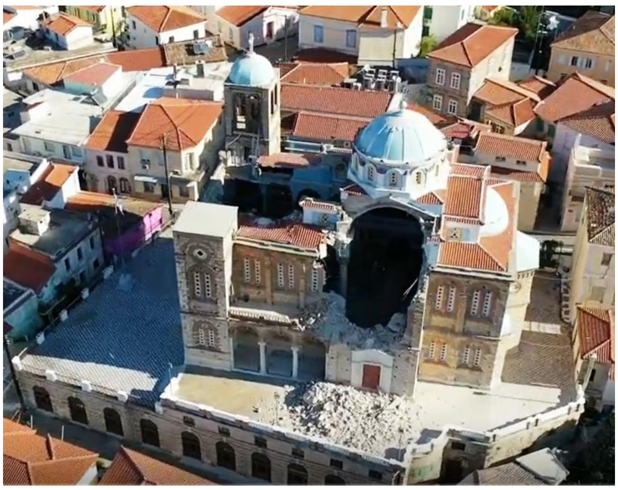

Figure 10. The collapsed parts of the domes at the West and North part of this church

Figure 11. The collapsed parts of the domes at the West and North part of the church

DOI: 10.23968/2500-0055-2020-5-4-03-17

the superstructure domes that are collapsing next in a sequential order. This is clearly indicated by figure 10 depicting the collapse of part of the Southern part of the transept by the out-of-plane collapse of the peripheral wall and the corresponding part of the superstructure. This is also indicated up to a point in figure 13. However, this time the partial collapse of the upper part of the peripheral wall was not followed by the sequential collapse of the supported superstructure.

4. The mechanism of the collapsed Western part of the central nave shown in figures 10 and 11 is more complicated. This may be due to the role of the ¼ spherical domes that bridges the space between the Western semi-cylindrical dome with the roof next to the central dome and the Western peripheral wall. This ¼ spherical dome is followed by a semi-cylindrical dome till it reaches the somehow elevated semi-cylindrical dome covered by the wooden roof with the tiles. The actual support conditions of this ¼ spherical dome are not known. Moreover, unknown are also the connection conditions of this part of the superstructure to either the adjacent dome or to this peripheral West wall. Figure 14 suggests that both these support and connection conditions failed and contributed to the loss of support of this part which, because of its considerable weight, could not be supported and this led to its collapse.

5. It is of interest to observe that a similar ¼ semispherical dome forms the cover of the East part of the central nave over the sanctuary. This part remained in its place despite its being damaged. This again can be partly explained because the East ¼ semispherical dome is not extended by an additional semi-cylindrical dome till it reaches the somehow elevated semi-cylindrical dome covered by the wooden roof with the tiles, as was described before for the Western part. Moreover, this part of the superstructure is supported by the East peripheral wall that is formed partly by the presence of an apse. It was demonstrated by previous research that the presence of such an apse provides considerable out-of-plane stiffness to a planar wall. Figure 15 depicts this part of the wall which, although heavily damaged, did not collapse.

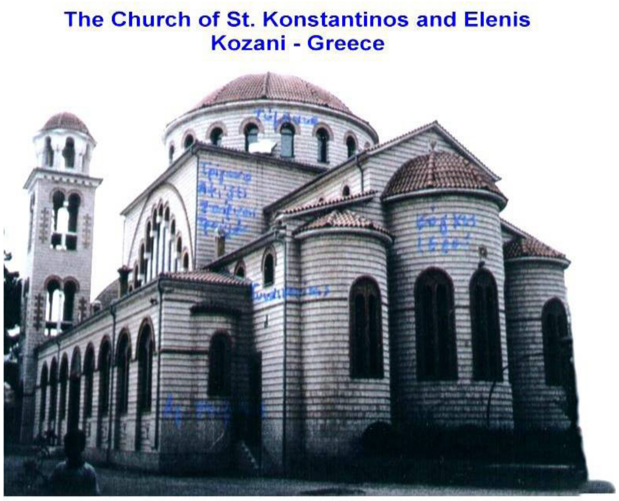

Figure 12. The church of St. Konstantinos and Eleni damaged by the 1999 Kozani-Greece earthquake (Manos et.al., 1997; Soulis and Manos, 2019)

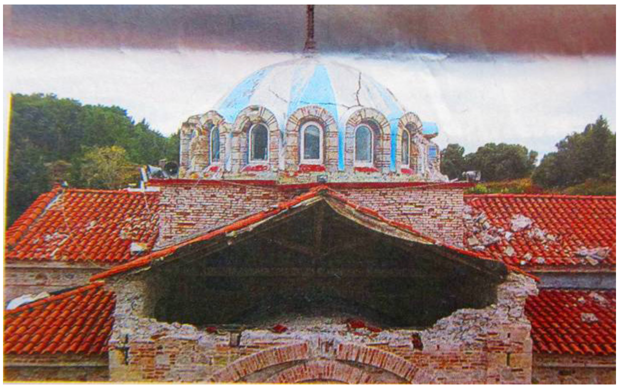

Figure 13. The church of Virgin Mary at the village of Konteika Samos island built in the 19th century. This church is again of the cruciform typology with a central spherical dome that sustained structural damage of the peripheral wall of typical morphology (Manos, Soulis, Diagouma, 2008)

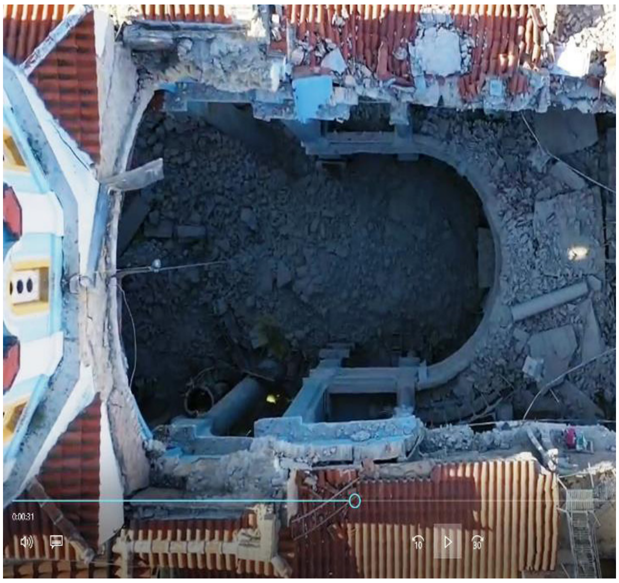

Figure 14. View of the collapsed Western part of the central nave

Figure 15. Damage of the Eastern peripheral wall with the Apse. Members of the emergency group salvaging the holy cross from the interior of this church

6. Another point to be made is related to the Northern part of the transept which did not collapse. Thus, its performance is different from that of the Southern part despite the fact that is almost of the same geometry. Any differences on the support and connection conditions between the two parts are not known. Moreover, unknown are any differences between the North and the South peripheral walls. One observation that must be underlined here is the foundation conditions of this church. As can be seen in figure 9 this church is built on a sloping hill in a way that a large portion of the structure extended from the longitudinal East-West axis of symmetry towards the South, rises from the low part of the slope. This leaves enough space under the floor level of the church for the formation of an extra story mainly at its Southern portion. It is not known how the flexibility of this story has influenced the dynamics of the whole system. Moreover, it must be investigated further whether the deformability of the supports of this part of the structure combined with the vertical component of the ground seismic motion contributed to the collapse of the Southern and not the Northern part of the superstructure. Figure 16 depicts the partial collapse of the church of St. Giorgio at L'Aquila-Italy (Croci, 1998; Limoge Schraen, Giry, Desprez, Ragueneau, 2015; Cerone, Viscovic, Carriero, Sabbadini, Capparela, 2001; Lagomarsino, 2011; Modena et.al., 2010). Certain similarities can be seen between the observations made here in figures 10, 11 and 14 and the L'Aquila damage depicted in figure 16.

Figure 16. The church of St. Giorgio damaged by the 6th of April 2009, L'Aquila-Italy, earthquake sequence (top and bottom)

7. Factors that may have contributed to this earthquake performance of this church are ones connected to past earthquake events and the type of maintenance works that were performed. It was already reported that two strong earthquakes occurred at Samos island in 1904 and 1954 with this church already built. Currently, temporary supports have been erected to prohibit any further collapse. Moreover, the reconstruction of this church was ensured by a recent visit at this site of the Prime Minister of Greece.

Old masonry buildings under conservation status

Figure 18 depicts the structural damage of low-rise buildings at Vathi sustained by the Samos earthquake of 30th of October 2020. Many of such buildings located at various urban areas in Greece are under special conservation status due to architectural features or historical significance. However, many of these buildings are left without either serious maintenance or the necessary

Figure 17. Typical damage to the peripheral masonry walls of "Basilica" churches from earthquake activity in Greece. At the top, a "Basilica" church at the village of Nisi from the Patras-Pyrgos earthquake of 8th June, 2008. At the bottom, a "Basilica" church at Karlovasi damaged from the Samos earthquake of 2020 (Manos and Kozikopoulos, 2015; Manos, Soulis, Karamitsios, 2012; Manos and Karamitsios, 2013; Manos, 2016; Manos, Kotoulas and Kozikopoulos, 2019; Manos and Kotoulas, 2019)

DOI: 10.23968/2500-0055-2020-5-4-03-17

retrofitting measures to upgrade their earthquake resistance. Moreover, a long-term debate has been taking place of the level of upgrading necessary, of the retrofitting techniques that could be allowed in such an effort and on who is going to pay for this retrofitting cost.

The conservation status when legislated is not accompanied with the necessary funds for the retrofitting effort. At the same time, when these building are privately owned the owners are very reluctant to undertake such a retrofitting cost because a different form of development involving the demolition of the old structure and the rebuilding of a new structure on the same premises is a much more profitable operation. This is especially true in places whereby the development from tourism changed drastically the financial activity and prospects in many Greek localities. To be found in many Greek islands as well as at the old part of city-centers in many Greek cities. In such instances the owners are expecting that an extreme event, e.g. a strong earthquake activity, will result in the destruction of such an old building resolving in this way on their benefit the conservation status burden when the severe structural damage and partial collapse will be the final result of such an extreme event. Many times, these buildings that are under conservation status change ownership and become the property of either the municipality or of a public agency. This is the case of the buildings shown in figures 19 and 22.

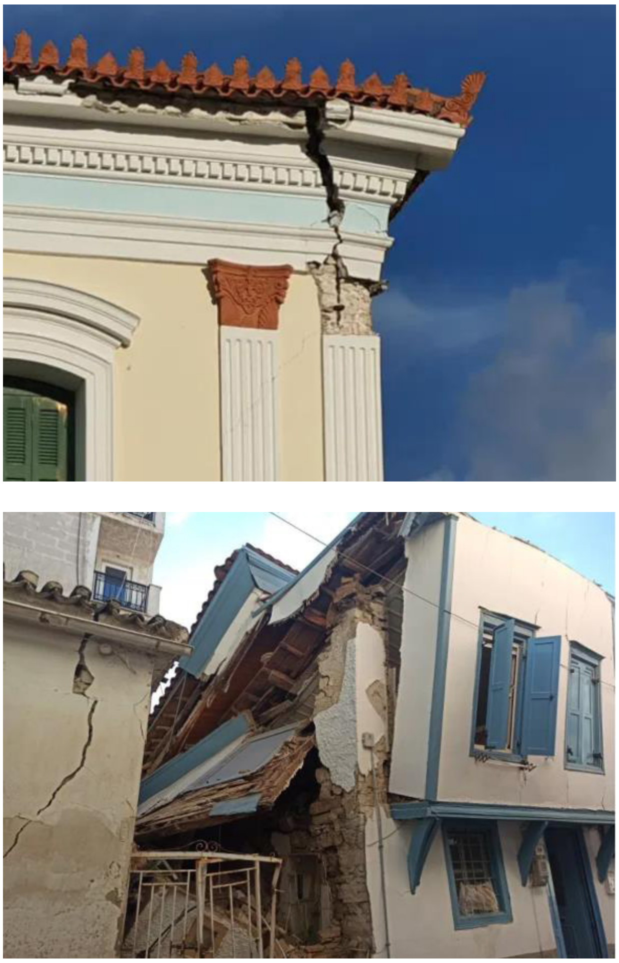

Figure 18. Damage of old low-story buildings at Vathi. In need of preservation because of particular architectural features

Figure 19. Old industrial buildings under conservation status

The buildings in figure 19 are old industrial buildings, named “Tampakika” being under conservation status in Karlovasi at Samos island. Initially, these buildings were built at the end of the 19th century, near the sea-shore of Karlovasi, as factories for the processing of leather. This activity was very prominent from 1880 till the beginning of World War II. After this, the leather processing in this part of the island started to decline having as a result for these buildings to be abandoned after few decades. Many old buildings were listed as part of cultural heritage under conservation status at the beginning of 1980. However, the effort for their maintenance and retrofitting has been, as explained before, relatively slow

A considerable number of the buildings depicted in figure 19 changed ownership and became part of the University of Aegean at the beginning of the 21st century. Recently in 2019 an agreement was signed between the Prefecture of Northern Aegean the Municipality of Samos and the University of Aegean, with the Technical University of Athens serving as technical consultant, to promote the retrofitting effort for these buildings. Unfortunately, the 30th of October Samos earthquake caused considerable structural damage to numerous buildings of this particular type, as shown in figure 22. The observed damage was of the typical form of loss of support and collapse of the wooden roof accompanied by the partial out-of-plane collapse of the long peripheral walls. The location of these buildings is shown in figure 21.

Old unreinforced masonry buildings that pose a potential threat for injuries

A final topic of interest is the partial collapse of low-story unreinforced masonry buildings causing the deadly injury of two young teenagers at the city of Vathi. Despite the low-rise of these buildings, the deadly event was caused by the considerable weight of the falling parts and the narrow streets in the old part of the city that inhibit any escape. This is depicted in figures 23 and 24. As a result, a special legislation is on the making for allowing the technical services of each municipality to order the demolition of old properties that are left without the proper maintenance of their owners and can be judged as representing a possible risk by partial collapse in the eventuality of a future earthquake. Again, for this type of problems the issue is partly technical and partly social-economic. The new legislature provides that the demolition cost will be initially paid by the municipality and then claimed back to be paid by the owners.

Numerical simulation of the earthquake behaviour of the old industrial buildings at Karlovasi

In this section, a summary of numerical predictions are presented focusing on the dynamic and earthquake response of a typical industrial building of the typology depicted in figures 19 and 22. The response of this type of structures is dominated by certain response mechanisms that

Figure 20. An old industrial building (The Markou Mill processing wheat to produce flour) in Veria-Greece, which now houses the Museum of Byzantine art of this city

can be characterized as “global”. These mechanisms include a) the connection of the wooden roof to the masonry walls b) the interconnection of the masonry walls at the corners and c) the potential of partial uplifting at the foundation due to tensile forces arising from excessive overturning moment response and uneven foundation settlements (Manos and Kozikopoulos, 2015; Manos, Kotoulas and Kozikopoulos, 2019). All these mechanisms are non-linear in nature and it is many times difficult to quantify them in order to include their influence in realistic numerical approximations. In what follows, an attempt is made to investigate the dynamic and earthquake response for a typical structure representing one of those old industrial building. In figure 25 the recordings of the earthquake ground motion, in terms of ground acceleration, velocity

Figure 21. Map indicating the location of the damaged old industrial buildings in Karlovasi - Samos

DOI: 10.23968/2500-0055-2020-5-4-03-17

Figure 22. The partial collapse of one of the industrial buildings at the seafront of Karlovasi

Figure 23. The partial collapse of old unreinforced masonry structures at Vathi that caused the death of two young teenagers

Samos Earthquake 30-10-2020, Damage from the main event at the city of Vathi, capital of the island of Samos. The most severe structural damage was related to unreinforced low-rise masonry buildings. Some of these buildings were left unoccupied and unmaintained for a long period

Figure 24. The partial collapse of old unreinforced masonry structures at Vathi that caused the death of two young teenagers

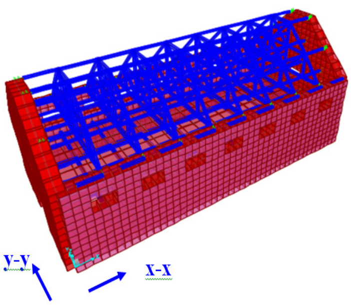

Figure 26. The numerical model of a typical industrial building of unreinforced masonry damaged by the 30th of October Samos earthquake (see figures 19 and 20)

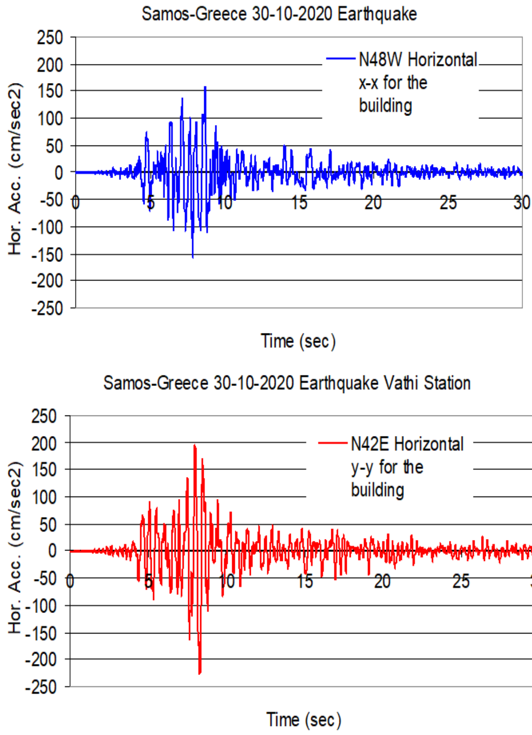

Figure 25. The recorded ground motion in the two horizontal directions by an instrument managed by the Institute of Earthquake Engineering and Engineering Seismology (ITSAK, see report (Preliminary report, October 2020; Preliminary report, November 2020)

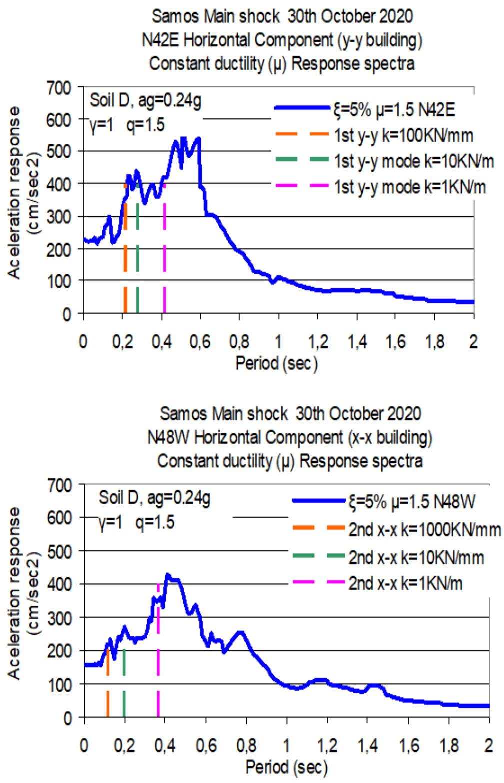

Figure 27. Acceleration response spectral curves for the two horizontal components of the earthquake ground motion recorded at Vathi during the 30th of October main event (see figure 25)

and displacement in the two horizontal directions are shown. Due to the location of the epicenter, the same epicentral distance of both the city of Vathi and the city of Karlovasi from the epicenter (see figures 1, 2, 3 and 21) and due to the generating mechanism of this earthquake that followed the almost East-West fault line, as can be seen from the aftershock sequence it can be reasonably assumed that the strong motion characteristics at Karlovasi would be quite similar to those of the recorded strong motion at Vathi.

The numerical model of this analysed industrial building with its wooden roof is depicted in figure 26. The wooden roof elements are connected with the masonry peripheral walls without transferring any bending moments. The stiffness of this connection is a parameter that is varied in this investigation. Summary results form various numerical dynamic spectral analyses are presented here. Each dynamic analysis is carried out based on the response spectral curves derived from the recording of the earthquake motion in the two horizontal directions at Vathi (Fig. 25). It was discussed, that this represents a realistic assumption. The corresponding spectral curves are depicted in figure 27. The response spectral curves in these figures were derived assuming a behaviour factor value equal to q=1.5 that is appropriate for unreinforced masonry structures.

The two-fundamental translational eigen-modes, derived from this numerical model, are depicted in figures 28 and 29. Figure 28 depicts the 1st translational mode in the direction y-y. The outstanding response in this mode is the out-of-plane response of the two longitudinal peripheral walls parallel to the x-x axis. Similarly, figure 29 depicts the 2nd translational mode in the direction x-x. The outstanding response in this mode is the out of plane response of the peripheral walls parallel to the y-y axis. The eigen-period values of these 1st and 2nd translational modes are shown in figure 27 depicting the response spectral curves in the N42E and N48W horizontal directions, respectively. A range of such eigen-period values are plotted in these two plots. The variation of these eigen-period values resulted from the variation of the stiffness of the connection of the wooden roof elements to the masonry peripheral walls, as indicated in these plots.

Figure 30 depicts the maximum displacement response for the load combination Dead + 0,3 ResSpec x-x + ResSpec y-y**.** As expected, the peak out-of-plane Uy displacement at the top of the longitudinal peripheral walls (the ones parallel to the x-x direction) become larger as the stiffness of the wooden roof with the masonry peripheral walls becomes smaller. The results of this relatively simplified numerical analyses explain, up to a degree, the observed damage sustained by these old industrial buildings during the recent 30th of October, Samos earthquake (Figure 22).

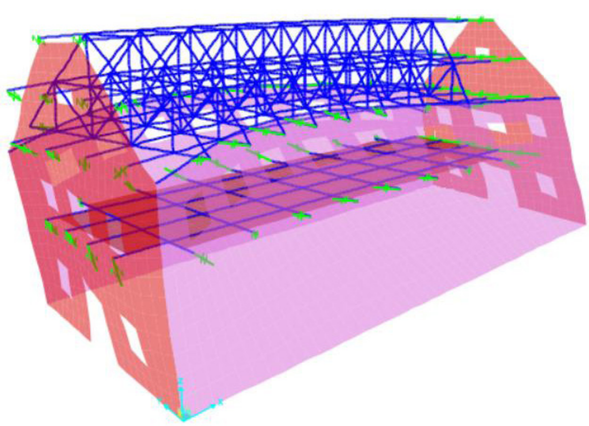

Figure 28. 1st translational eigen-mode. Out of plane response of the peripheral walls parallel to the y-y axis

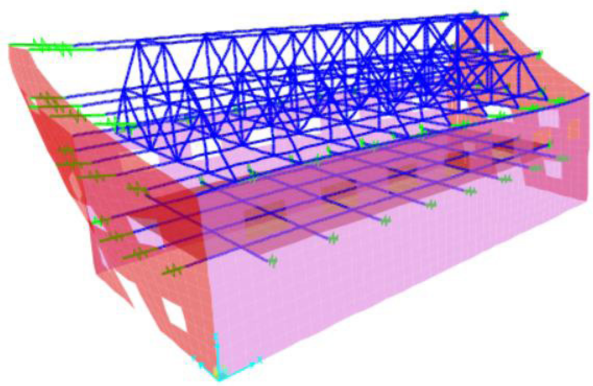

Figure 29. 2nd translational eigen-mode. Out of plane response of the peripheral walls parallel to the x-x axis

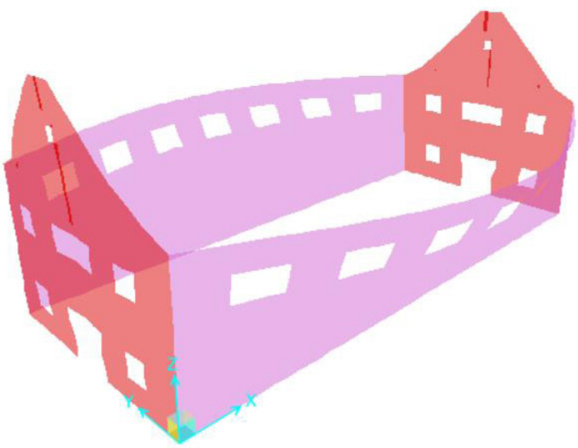

Figure 30. Displacement response from the load combination Dead + 0,3 ResSpec x-x + ResSpec y-y

DOI: 10.23968/2500-0055-2020-5-4-03-17

Conclusions

- The recent earthquake sequence in the Greek island of Samos gave the opportunity of assessing the earthquake performance of various types of structure in Greece. It can be stated that the enforcement in 1995 of the "New Greek Seismic Code" together with the provisions of the Euro-Codes has substantially increased the safety level of structures against earthquakes. A similar successful effort has been made through various educational channels for upgrading the relevant design and construction practices of professionals as well as the relevant knowledge of the general public in earthquake preparedness measures. A significant expansion of the strong motion network of accelerographs that covers the whole of Greece provides very important information on the characteristics of the earthquake strong ground motion that is very useful in assessing the consequences of the intense earthquake activity to the built environment. The relevant data base is enriched with valuable information on the characteristics of the earthquake strong ground motion that is very useful to designers and contractors.

- For RC multi-story buildings which were constructed prior to the enforcement of the New Greek Seismic Code Provisions (before 1995) certain "structural deficiencies" have long been identified that pose high risk towards seismic safety. One particular "structural deficiency" is that of a "soft" ground floor for RC multi-story buildings resulting in amplified shear force demands for the ground floor columns at an amplitude that can not be met by the corresponding shear capacity due to the shear reinforcing detailing of these ground floor columns according to the old code provisions. Another similar structural deficiency is the "accidental" formation of short columns in RC framed structures once again by building strong infill in various openings. These non-ductile response "structural deficiencies" combined with irregularities in plan and elevation as well as with strong earthquake ground motions, which often lead to demands exceeding the corresponding demands assumed in design, result in structural damage that caused in the past serious fatalities, fortunately in small numbers. A specific code with provisions focusing on the assessment of the vulnerability of such structures as well as on provisions relevant to the structural upgrading has been published for some time. However, the retrofitting effort is colossal as the buildings in this category are numerous (Organization of Earthquake Planning and Protection of Greece (OASP), 2001; Manos and Katakalos, 2013).

- Another high seismic risk category includes old structures under conservation status including cultural heritage structures. A large number of such structures are relatively old Christian Greek Orthodox churches, built with unreinforced masonry, which have sustained heavy structural damage during the last 40 years. They represent special cases because their structural system is more complex than that of ordinary buildings. Similar difficulty exists in assessing for such structures the capacity of their structural members as well as in applying acceptable retrofitting solutions that respect the principles of compatibility and reversibility. Moreover, various social-economic complications render the various retrofitting attempts even more difficult and time-consuming. This study tries to highlight some of these issues and to present some of the numerical tools to deal with such structures.

- Another source of seismic risk that can result in human loss was highlighted by this earthquake event. It is generated by old and weak unreinforced masonry structures which are left un-occupied and not maintained by their owners due to various social-economic non-incentives and complications. Legislation is currently proposed to tackle this problem. Another group of high seismic risk buildings are the ones that are not designed by earthquake resistant design provisions in localities that are far away from the authorities. Additional legislation, currently enforced, aims to reduce the seismic risk arising from this group of buildings.

- Numerical tools combined with realistic measurements of the seismic forces generated by a strong earthquake ground motions can be utilized to explain the observed structural damage. They can also be utilized in the subsequent retrofitting effort.

*To the memory of Nikolaos Simos, PhD, PE, Senior Scientist Emeritus\
Brookhaven National Laboratory, U.S.A.*

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