Advanced Materials Research Vols. 133-134 (2010) pp 765-770

doi:10.4028/www.scientific.net/AMR.133-134.765

Seismic Vulnerability of Historical Structures:Damage State of the Abruzzo (Italy) Churches in the Sequence of the April 2009 Earthquake

SILVA B[1, a], COSTA C Q[2,b], DA PORTO F[3,c], VALLUZZI M R[4,d] and MODENA C[5,e]

[1,3,5]Department of Construction and Transportation Engineering, University of Padova, Padova, Italy

[4]Department of Architecture, Planning and Survey, University of Padova, Padova, Italy

[a]silva@dic.unipd.it, [b]catarina.costa@fe.up.pt, [c]daporto@dic.unipd.it, [d]valluzzi@dic.unipd.it

[e]modena@dic.unipd.it

Abstract Each earthquake represents a particular moment in the history of the affected region. The seismicity in Italy reaches frequently high values, what makes it a country particularly affected by this kind of natural disasters. Historical constructions (in particular masonry ones) are structures that show a high vulnerability to the type of loads introduced in the sequence of a seismic event.

This paper focus on the effects of the 6th of April 2009 earthquake, that affected the region of Abruzzo (Italy), over the historical buildings of the region, in particular churches, by establishing a set of different objectives directed to the understanding of their structural behavior and to the assessment of the extent of post seismic damage in this structures.

During the emergency period that followed the earthquake, many churches and other historical constructions (towers, walls, palaces, etc…) were surveyed, according to the official 1st level damage survey forms for Cultural Heritage (C.H.), by the workgroup of the University of Padova (UNIPD). The information collected from these surveys was later inserted and organized in a database. A statistical work is presented, illustrating the referred information and focusing on the data related with the damage assessment of the considered monuments. This work presents an intuitive overview of the seismic effects over the surveyed churches, allowing not only to better understand the response of these structures to this particular action, but also correlating the earthquake data with its effects on the churches.

Keywords: Abruzzo, earthquake, damage, vulnerability, church

Introduction

As a consequence of the 6th April 2009 earthquake in L'Aquila (Abruzzo) appeared the need to perform an emergency safety analysis of all the buildings, from simple houses to monumental buildings, in the affected area. The UNIPD, along with many other institutions, started collaborating in the emergency operations since the beginning. Due to its area of expertise the UNIPD workgroup focused on the viability assessment of historical buildings.

The first phase of this work consisted on surveying the monuments of the region, in particular churches and palaces, through the compilation of the 1st level damage survey forms for C.H., in order to define an intervention priority list based on their viability and damage index.

According to the data available by the Italian Civil Protection (Italian Civil Protection 2010), until 25th of October 2009, 1677 historical buildings were surveyed, from which 973 were churches, 649 were palaces and the remaining 55 correspond to other typologies of historical buildings, such as towers, fountains, etc…

This paper will focus on the particular case of churches. Given their cultural importance and necessity to be preserved, they gained priority in the inspections, during the first emergency period. Actually, during this referred period 80.0% of the total surveys were churches.

The data gathered by the UNIPD, during the 1st level technical surveys performed to the churches in the region of Abruzzo, in result of the 6th April earthquake, was later inserted in a database, in order to have the information organized and to allow an easy access to these results. After the preparation of the database, a statistical analysis focusing on the churches was carried out, in order to understand and correlate the earthquake data with its effects on this type of structures, (Costa 2009).

Seismic Event

On April 6, 2009 at 3:32 a.m. local time, an earthquake hit the central region of Italy, more precisely the region of Abruzzo, near the city of L'Aquila. This earthquake presented a moment magnitude of 6.3 Mw and a shallow focal depth, of approximately 8.0 to 9.0km, according to (INGV 2010). The epicenter was located 10.0Km West of L'Aquila and 95.0km NE of Rome, (EERI 2009) and (EEFIT 2009).

As can be seen in Figure 1, (INGV 2010), three events with M>5 occurred on 06/04 (Ml=5.8), 07/04 (Ml=5.3) and 09/04 (Ml=5.1). Events with 3.5≤Ml≤5 amounted to 31. More than 20.000 quakes have been recorded, since the mainshock, by the INGV station placed in the underground shelter of L'Aquila Castle. These aftershocks covered an area of more than 30.0km, extending in NW-SE direction, along the Aterno Valley and consistent with the direction of the principal known active faults of the area. The quakes mainly originated in the surface crust, in a depth between 10.0 and 12.0km. The main shock originated from the Paganica fault, 15.0km long in NW-SE direction.

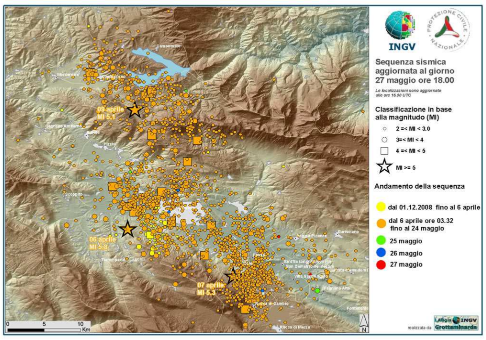


Figure 1: Seismic sequence in the region of Abruzzo, (INGV 2010)

Data Treatment

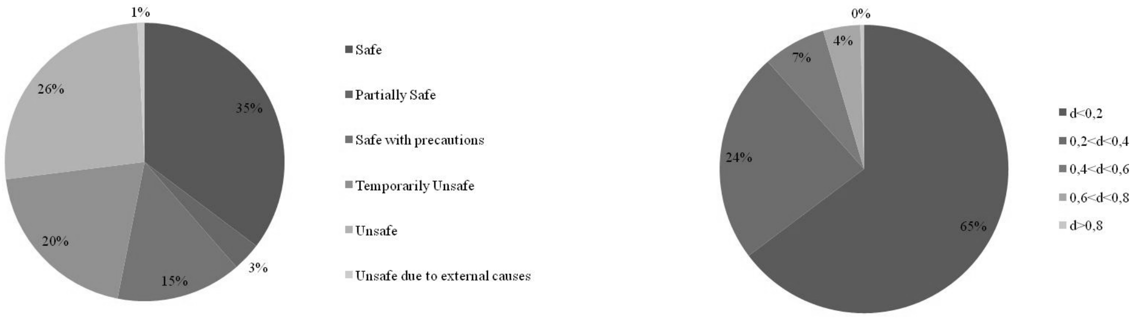
In this point it is going to be presented the elaboration and results of the statistical analysis of the information gathered by the UNIPD during the 1st level technical surveys performed to the churches in the region of Abruzzo, in result of the 6th April earthquake.

The UNIPD workgroup collaborated on the survey of 241 churches which corresponds to approximately 25.0% of all the surveyed churches, (Italian Civil Protection 2010). Of all the churches included in the database (241 in total) 35.0% were considered safe, 15.0% safe with precautions, 3.0% partially safe, 20.0% temporarily unsafe, 26% unsafe and only 1.0% unsafe due to external causes (Figure 2a).

After the definition of the possible mechanisms that can be activated and the level of each one, it is possible to calculate the damage index (I_d) of the structure. As presented in equation (1), according to the macro-seismic scale EMS98, the damage index of a certain structure is calculated based on the activated mechanisms (n) and on the total level of damage. This index presents a value that various between 0 (undamaged state) and 1 (total collapse) and measures the average damage of the church. It is a very useful parameter in the emergency stage, as it gives a hierarchy of the extent of the damages of the affected churches, what represents a fundamental categorization for the organization and intervention in the post-earthquake emergency.

$$I_d = \frac{1}{5n} \sum_{k=1}^{28} d_k \qquad (1)$$

In the following analysis, this interval of damage was divided in 5 subintervals, in order to allow a more intuitive interpretation of the results. From the analysis of the graphic presented in Figure 2b it is possible to conclude that the majority of the analyzed churches (65.0%) present a low damage index (below 0.2). A considerable percentage of churches (24.0%) are comprised on the 2nd interval of damage index (values between 0.2 and 0.4) presenting a medium level of damage. 7.0% of the churches present an intermediate index damage while other 4.0% reach values between 0.6 and 0.8, which are already very high. Less than 1.0% of all the surveyed churches have a damage index higher than 0.8, correspondent to a situation of almost total or even total collapse.



(a) *(b)*

Figure 2: (a) Viability percentage (b) Damage index distribution

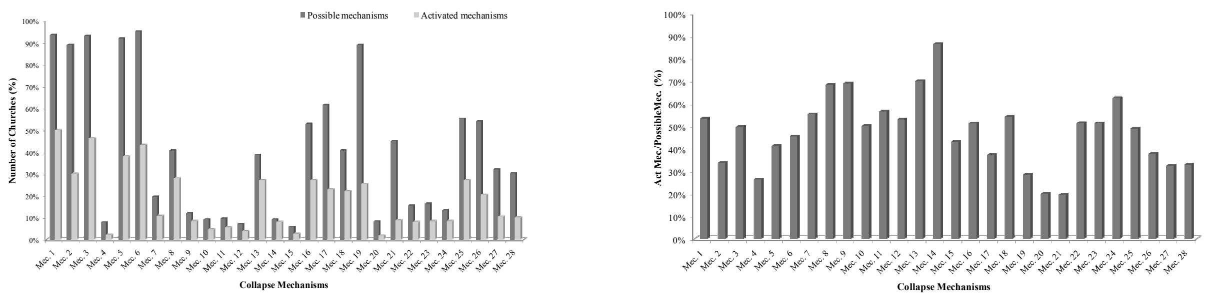
Although many times is expected a relation between the damage index and the safety, in this case this relation is not verified. However, it is possible to establish a direct relation between the damage index and the overall damage in the structure.

In the cases where a high damage index is obtained, it is almost sure that the church is unsafe, because it means that the entire church shows a considerable damage. In the other cases (when the damage index is low) two situations are possible. Either the damage is low/moderate but affects a big percentage of the church, or the damage is low or inexistent in the biggest part of the church, but shows a high value for a particular mechanism(s). In the first case, the church can still be considered safe, because the damages are not significant and probably will not lead to the collapse or unsafety of the structure. In the second case, although most of the church does not show a potential source of danger, a small part of it can be in danger, and it will define the unsafety of the whole structure, although in general the damage index is low. For this reason, it is not possible to define a direct relation between these two indicators (damage index and safety) but, instead, each case should be analyzed and studied individually.

It is also interesting to analyze the most frequent collapse mechanisms that can be activated, depending on the church configuration, (Figure 3a). As expected, some of the mechanisms can be activated in most of the churches, while others are present only in on few.

The mechanisms number 1, 2, 3, 5, 6 and 19 appear as the most frequently possibly activated. These mechanisms are all related with the basic composing elements of a church, the ones that are always present: (i) frontal façade (the first three); (ii) nave, in particular its transversal response; (iii) lateral walls and (iv) roof. Most of the churches present in the database have only one nave, and this is the reason for the lower values of some mechanisms, which are only present in churches with more than one nave. This is the case of mechanisms number 7 (Longitudinal response of the columns) and 9 (lateral nave vaults). Also the mechanisms associated with the transept (10, 11, 12 and 20) have low values because most of the churches do not have this element in their structure.

In Figure 3b it is possible to analyze the percentage of activated mechanisms in the cases that it is possible their activation. According to the results although mechanism number 14 (related with the dome) is rarely possible, most of the times it is activated (around 85.0% of the cases). The most frequent mechanisms (number 1, 2, 3, 5, 6 and 19), although frequently possible to occur, are only activated around 50.0% of the times, or even less.



(a) *(b)*

Figure 3: (a) Possible and activated collapse mechanisms. (b) Percentage of possible mechanisms in fact activated

It is notorious that all the mechanisms connected with the vaults (number 8, 9, 12, 18 and 24) show a percentage of activation between 53.0 and 69.0%, which is high. This is indicative of the vulnerability of the vaults, elements that are most of the times damaged. Also the triumphal arch (mechanism number 13) is activated most of the times, 70.0%, which is a considerably high value.

Conversely, the mechanisms related with the roof of the different parts of the church (number 19, 20 and 21) have low activation percentage (29.0% in the case of the central nave roof and equal or lower than 20.0% in the transept and apse cases).

By dividing the total points of damage of each mechanism by the number of churches where the respective mechanism is activated, the average damage for each mechanism is obtained (Figure 4). Although the values are not uniform, they vary approximately between 1.6 and 3.0 in a scale between 0.0 and 5.0, where 5.0 correspond to the collapse of the structure.

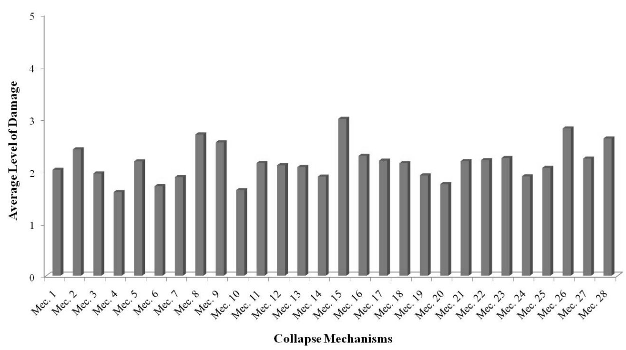


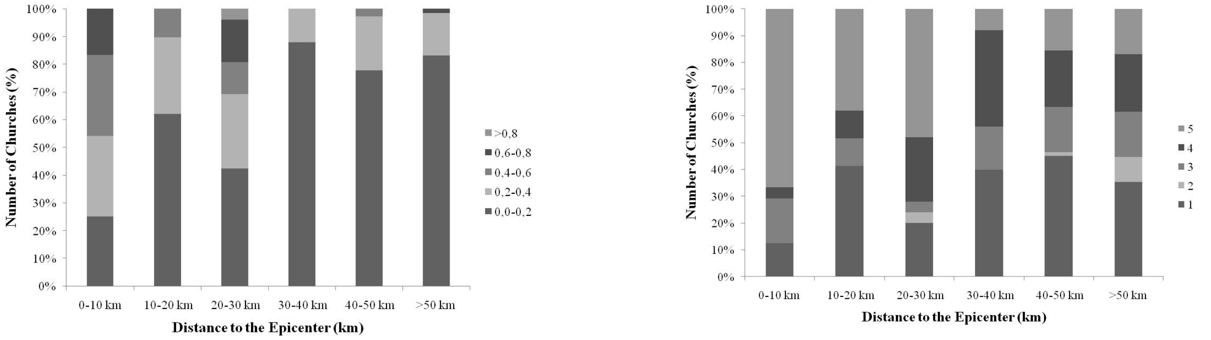
Figure 4: Average damage for each activated mechanism

The mechanism 15, that regards the lantern, presents the higher damage index average ($I_{dm} = 3.0$), and as so, it is possible to conclude that this is a highly vulnerable element. The projection elements, such as statues and pinnacles, also present a high vulnerability in agreement with its usual poor supporting and equilibrium conditions. The mechanism 26 related with these elements presents a $I_{dm} = 2.82$. Also in the case of mechanism 28, that regards the belfry, the average damage index is also relatively high when compared to the others ($I_{dm} = 2.63$), and as so, presents itself as a very vulnerable element. In what concerns these two last mechanisms (26 and 28), their high level of average damage index and of activation is easily corroborated by the fact that, almost all the churches, that present this type of constructive elements, underwent an intervention that comprised their temporary stabilization, as part of the provisionary post earthquake interventions, (Vigili del Fuoco 2010) and (Modena et al. 2009).

The mechanisms 8 and 9 (central and lateral naves vaults) show a high average damage index of 2.70 and 2.55, respectively, and are activated in approximately 70.0% of the cases.

On the other hand, the mechanism 4, that concerns the porch and the shear mechanisms in the lateral walls (mechanism number 6), present a low damage index average, as well as the transept and central nave roofs (19 and 20), what can be indicative of the lower vulnerability of these elements to the kind of loads introduced by this earthquake.

Considering the data collected, it was of interest to analyze the relation between the damage index of the surveyed buildings and its viability in respect to the distance of these same buildings to the epicenter of the 6th of April 2010 seismic event, Figure 5.



(a) *(b)*

Figure 5: (a) Relation between the damage index and the distance to the epicenter. (b) Relation between the viability and the distance to the epicenter (1 - safe; 2 - partially safe; 3 - safe with countermeasures; 4 - temporarily unsafe; 5 - unsafe)

In Figure 5a it is possible to observe that, in the first area considered (up to 10.0km from the epicenter), the percentage of churches with a damage index below 0.4 is the lowest of all the considered intervals. Curiosly, this is not the area that presents the highest damage index, but it is the area with the biggest percentage of cases in the range from 0.4 to 0.8, (≈55.0%), which is already a very high level of damage, indicative of which is the condition of the churches in this area, in general very damaged.

On the range from 10.0 to 20.0km its possible to observe a noticeable decrease on the damage index in respect to the first interval. Aproximatly 60.0% of the churches in this area show a damage index below 0.2 and almost 90.0% bellow 0.4. Only 10.0% of the churches present a relatively high damage index (0.4 to 0.6).

Between 20.0 and 30.0km, the damage index shows higher values, in some cases it even surpasses 0.8. There is also a high percentage of churches with a damage index in the range 0.6 to 0.8. These higher values can have different explanations, depending on each particular case, but many times they are due to site amplification effects, in particular areas, which lead to a higher seismic action in these locals and, consequently, a higher damage index in the correspondent churches. Another possible explanation, although not confirmed, can be related with the fact that these villages around the main city (L'Aquila) were in general reserved to people less wealthy, what can have imposed a poorer quality of the materials and the construction of the churches in these places and, consequently, a worst response to the earthquake. On the other side, the center of L'Aquila used to be occupied mainly by people with a lot of possessions, who could apply their money in the construction of strong and imponent churches that nowadays show a better seimic response. This question is here presented as an hypothesis, which could be an interesting subject to deepen in further studies. Still in this range (20.0 to 30.0km), aproximatly 70.0% of the structures present damage index lower than 0.4.

Between 30.0 and 40.0km the damage index reduces drastically, the same can be said for the sucessive considered intervals, 40.0 to 50.0km and >50.0km. In these intervals almost all the churches have a damage index below 0.4, being that 80.0 to 85.0% of the cases are under 0.2.

In Figure 5b the relation between distance to the epicenter and the safety of the structures is described. On the first three ranges, defined for the epicentral distance, the percentage of unsafe churches is higher, in particular on the first range (up to 10.0km from the epicenter) where the percentage amounts to 65.0% of unsafe with an adicional 5.0% of temporarly unsafe cases. On the epicentral range, 10.0 to 20.0km, the distribution of the safe (including the safe and the ones safe but with percautions) and unsafe (including the unsafe and the temporarly unsafe) structures is more or less 50.0/50.0. As for the interval 20.0 to 30.0km the percentage of unsafe churches (including the temporarly unsafe) is similar to the percentage of the first interval with the difference that, in this case, the temporarly unsafe churches present a higher percentage (≈25.0%).

On the last three considered intervals it is noticeable a sharp reduction in the unsafe structures (variation between 8.0 and 17.0%), while the percentage of temporarly unsafe structures increased. On the other hand, the number of structures considered safe increased, varying between the 35.0 and the 45.0%.

Conclusions

The work developed along this year, following the earthquake, allowed to study its effects and to draw some conclusions about the damage in the surveyed monuments. This earthquake was very damaging in some of the monuments of the region, which were completely or partially destroyed, especially the ones located closer to the epicenter (around the city of L'Aquila). Generally, with the increase of the distance to the epicenter the effects of the seismic action became lower, however, in some cases located not so close to the epicenter, the effects were amplified maybe due to the geological conditions of the site, especially in the region of the Atterno Valley. Some of the most damaged villages are located in this area (Castelnuovo, Onna, San Gregorio and Poggio Picenze), which evidences the site amplification on soil deposits. The reverse is sometimes verified too, as in the case of the S. Pietro church, in Coppito, where the effects were not so damaging, what can probably be explained by attenuation effects due to the geological properties of the soil.

From the statistical analysis performed over the collected data, it was also possible to conclude that there are some mechanisms that are in general more easily activated in respect to others, which is the case of the mechanisms number 8, 9, 24 (central nave, lateral nave and chapel vaults), triumphal arch (mechanism 13) and dome (mechanism 14). Conversely, in general, the elements related with the roof (nave, transept and apse) and with the tower show lower percentages of activation.

A general overview on the average damage index in each element, allows concluding that the elements 8, 15, 26 and 28 (central nave vault, lantern, projections and belfry) have always a high level of damage. On the other hand, numbers 6 and 7 (shear mechanism in lateral walls and longitudinal response of the structure) present low levels of this ratio. The element number 8 (central nave vault) is then, one of the most vulnerable elements found in the inspected churches, once it has the highest percentage of possible activated mechanism and also the highest average damage index.

References

[1] (2010) The INGV website. [Online]. Available: http://portale.ingv.it/portale_ingv/

[2] (2010) The Italian Civil Protection website. [Online]. Available: http://www.protezionecivile.it/

[3] (2010) The Vigili del Fuoco website. [Online]. Available: http://www.vigilfuoco.it/

[4] Costa, CQM (2009). "*Seismic Vulnerabilty of Historical Structures. Damage state of the Abruzzo churches in the sequence of the 2009 earthquake.*" MSc Thesis, Erasmus Mundus Advanced Master in Structural Analysis of Monuments and Historical Constructions, University of Padova.

[5] EEFIT (2009). "The L'Aquila, Italy earthquake of 6th of April 2009. A Preliminary field report by EEFIT." [Online]. Available: http://www.istructe.org/eefit/db/451.asp.

[6] EERI Special Earthquake Report (2009). "The Mw 6.3 Abruzzo, Italy, Earthquake of April 6, 2009." [Online]. Available: http://www.eeri.org/

[7] Modena, C, and Binda, L (2009). "Monumental historical buildings: Protection of the cultural heritage in the post-earthquake emergency." *Progettazione Sismica*. L'Aquila 6 April 2009, ore 3.32. nº3, 2009.