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EARTHQUAKE RISK SCENARIOS FOR MONUMENTS IN BARCELONA, SPAIN

Janira IRIZARRY[1], Xavier GOULA[2], Teresa SUSAGNA[3], Antonio ROCA[4] and Fructuós MAÑA[5]

SUMMARY

For the past years the city of Barcelona has been participating in the European project "RISK-UE: An advanced approach to earthquake risk scenarios with applications to different European towns" (Mouroux [1]) which consisted on defining and applying methodologies for the seismic risk assessment in seven European cities. The city of Barcelona is located in a zone of moderate seismicity. In the past, this zone had been affected by strong regional historical earthquakes. Barcelona is a densely populated city whose main building stock was constructed prior to the application of any seismic code in Spain and mostly over soft soils. Recently, these facts have awakened the necessity of a seismic risk assessment for the city.

The seismic hazard assessment was evaluated using both deterministic and probabilistic approaches. The deterministic approach was defined in terms of both macroseismic intensity and acceleration spectral values, while the probabilistic approach was defined only in terms of acceleration spectral values. The vulnerability of Barcelona's building stock was evaluated using two methods. The vulnerability index method, in terms of intensity, is based on the statistical study of the damage levels observed in similar types of buildings during European strong earthquakes. The capacity spectrum method is based on the construction of capacity curves representative of the building typologies available in the city and their comparison with the demand imposed by the earthquake on the buildings.

The RISK-UE methodologies were applied to both current and monumental building in the city of Barcelona, this article shows the results obtained in the damage assessment of the most important monuments of the city.

INTRODUCTION

With a total of 1,503,451 inhabitants, Barcelona, the capital of Catalonia, is located on the northeast coast of Spain as shown in Figure 1. Bounded by the Collserola ridge and rivers Besós and Llobregat, the city has an area of almost 100 km^2 giving it a population density over 15,176 persons/km^2.

[1] Junior Researcher, Geological Survey, Institut Cartogràfic de Catalunya, Spain. Email: jirizarry@icc.es
[2] Head of Seismology, Geological Survey, Institut Cartogràfic de Catalunya, Spain. Email: xgoula@icc.es
[3] Senior Researcher, Geological Survey, Institut Cartogràfic de Catalunya, Spain. Email: tsusagna@icc.es
[4] Head of Geological Survey, Institut Cartogràfic de Catalunya, Spain. Email: roca@icc.es
[5] Director of Research and Development, Institut de Tecnologia de la Construcció de Catalunya, Spain. Email: fmanya@itec.es

Figure 1. Location of the city of Barcelona.

By the end of the 4th century, Barcelona was a fortified walled town, covering about 10.5 Ha. Barcelona's evolution into a big city began in 1868 when adjacent towns were added to the city becoming its actual districts. Between 1910 and 1930, the population grew from 587411 to 1005565 inhabitants. This population explosion was accompanied by a highly productive construction period. So most of the city's building stock was constructed when no seismic codes were available. The combination of very old buildings constructed without seismic conscience and a highly populated and active city can be extremely risky under the effects of even a moderate earthquake.

The seismicity of the Catalonia region is moderate when compared to other regions in the Mediterranean Sea. Between the 14th and 15th centuries, the seismic activity reported in Catalonia was over its usual average and several earthquakes caused damages in Barcelona. On February 2, 1428, an earthquake in the Pyrenees with a local magnitude of 6.5 and an epicentral distance of 90 km damaged slightly some churches at Barcelona. In 1448 another earthquake with a local magnitude of 5.5 cracked a wall in a castle. During the 20th century, a few earthquakes had been felt in the city with a maximum intensity of IV degrees in the MSK intensity scale.

The damage scenarios presented in this work are evaluated using the methodologies developed within the European project "RISK-UE: An advanced approach to earthquake risk scenarios with applications to different European towns" (Mouroux [1]). The seismic hazard was defined using both probabilistic and deterministic approaches and a building typology matrix was constructed for the city. The vulnerability of both current buildings and monumental buildings was evaluated and expected damages were obtained for all the considered buildings. The vulnerability of lifelines was not evaluated on detail because of the lack of detailing information and the fact that seismic hazard is not considered to cause many problems to lifelines.

SEISMIC HAZARD ASSESSMENT FOR BARCELONA CITY

The seismic hazard for the city of Barcelona was evaluated using both deterministic and probabilistic approaches including site effects. The deterministic hazard, based on the maximum historical earthquakes felt in the city, was presented in two levels: intensity and spectral acceleration values. The probabilistic seismic hazard was evaluated only in terms of spectral acceleration.

Deterministic seismic hazard was evaluated based on the historical earthquakes that had affected the city of Barcelona. The historical earthquakes of Girona in 1428 (I = IX) and Cardedeu in 1448 (I = VIII) were chosen as reference earthquakes and are shown in Figure 2.

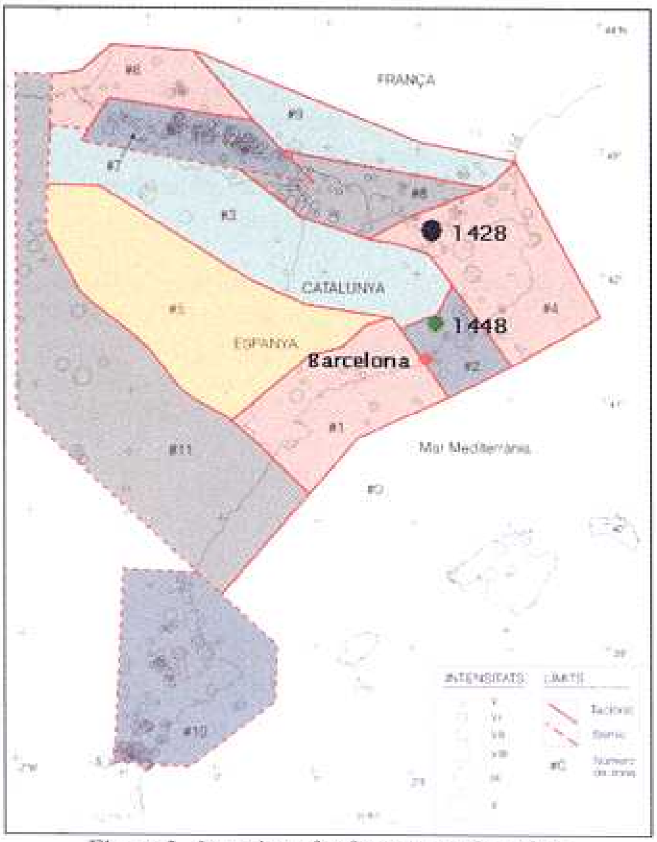


Figure 2. Location of reference earthquakes.

The deterministic seismic hazard in terms of intensity is defined based on the 1448 Cardedeu earthquake and the intensity attenuation relationship adjusted by Secanell [2] for the Catalonian region. The deterministic seismic hazard map for a mean rock soil obtained is shown in Figure 3. The deterministic seismic hazard in terms of spectral acceleration was evaluated using the combined effect of the two reference earthquakes. Ambraseys [3] relationship was used for the spectral acceleration attenuation. The deterministic acceleration response spectra obtained for the city of Barcelona is shown in Figure 4.

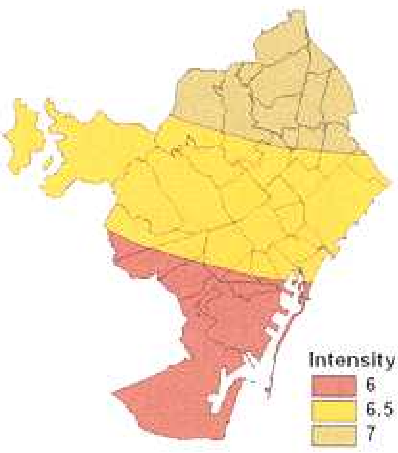


Figure 3 – Deterministic seismic hazard map in terms of intensity.

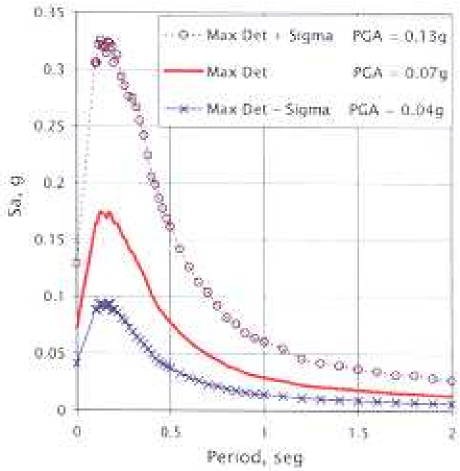


Figure 4 – Deterministic seismic acceleration response spectra for the city of Barcelona.

The probabilistic seismic hazard was performed using the seismotectonic zonation (Figure 2) and seismicity parameters developed by Secanell [2]. The computer program CRISIS 99 from Ordaz [4] was used to evaluate the probabilistic seismic hazard using the Ambraseys [3] attenuation relationship. Figure 5 shows the acceleration response spectra obtained for different return periods compared to the deterministic acceleration spectra. The deterministic acceleration spectra obtained is lower than the probabilistic acceleration spectrum associated to a 475 year return period. The deterministic acceleration spectrum is similar to a probabilistic spectrum for a 200 year return period.

Site effects are included both in the probabilistic and deterministic seismic hazard assessment following the seismic zonation of Barcelona based on local effects from Cid [5] shown in Figure 6. In the deterministic hazard assessment in terms of intensity were considered by adding a 0.5 intensity degree for soft soil zones as done by Secanell [2], while for the hazard assessment in terms of spectral acceleration the site effects are considered by means of spectral amplification factors. The deterministic seismic hazard map with soil effects in terms of intensity is shown in Figure 7.

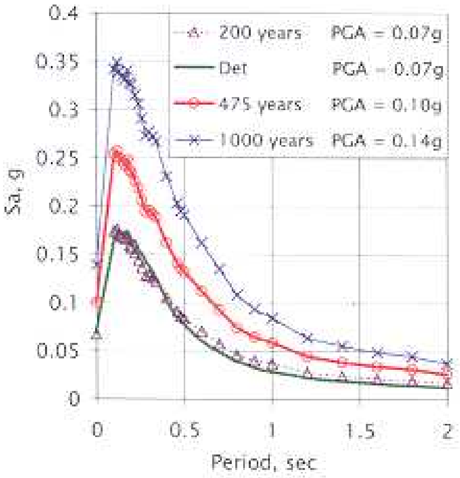


Figure 5 – Probabilistic and Deterministic acceleration response spectra for Barcelona.

Figure 6 – Seismic Zonation based on local effects from Cid [5].

The spectral amplification factors were calculated from the transfer function data available from Cid [5]. The transfer function of each soil zone was convoluted with real earthquake recordings having an acceleration response spectrum similar to the acceleration response spectra obtained for rock sites. Acceleration response spectra with soil effects for each soil zone were obtained from this convolution. The amplification factors, shown in Figure 8 were compared to the amplifications recommended by the current version of Eurocode 8. The comparison showed that the amplification factors are within the ranges of amplification used in Eurocode 8.

The amplification factors were applied to both the deterministic and probabilistic acceleration response spectra for a rock in order to obtain the corresponding acceleration response spectra with soil effects expected on each soil zone of Barcelona. Figure 9 shows the recommended acceleration response spectra with soil effects using the probabilistic approach. The results from the seismic hazard assessment with site effects are also expressed in the form of GIS maps for a return period of 475 years.

The seismic hazard in terms of spectral values is also shown in the form of demand spectra. The acceleration-displacement response spectra (ADRS) for the different soil zones were calculated and corresponding analytical formulations were developed in order to make easier its application in vulnerability assessment. Figure 10 shows the analytical acceleration ADRS for the probabilistic approach.

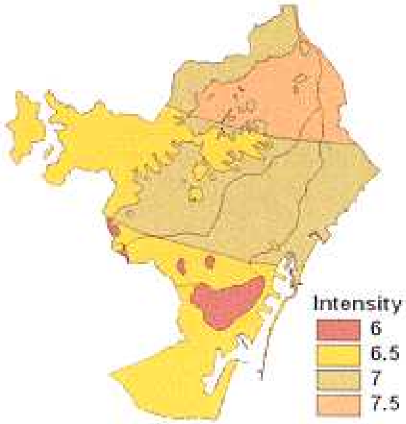


Figure 7 – Deterministic seismic hazard map with soil effects in terms of intensity.

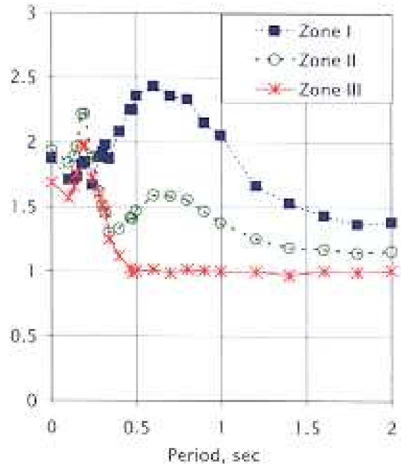


Figure 8 – Spectral amplification factors for Barcelona's soil zones.

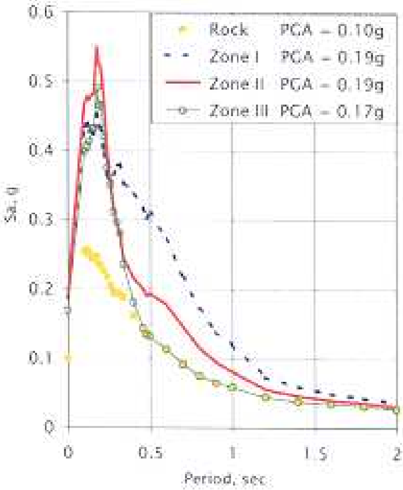


Figure 9 – Probabilistic acceleration response spectra with soil effects for a return period of 475 years.

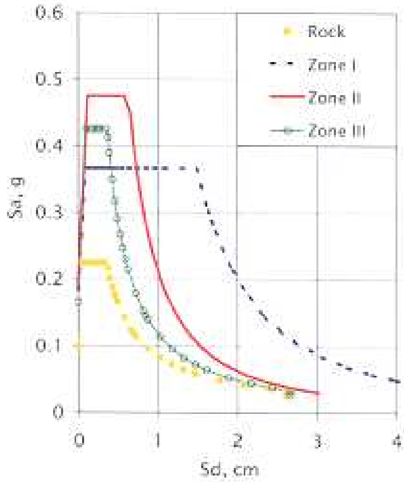


Figure 10 – Analytical form of the probabilistic ADRS for Barcelona's soil zones.

No induced hazard effects like landslides, settlements, liquefaction or lateral spreading had been observed during the past earthquakes that had affected the city of Barcelona. A deterministic peak ground velocity GIS map, elaborated using Boomer [6], showed that the expected levels of peak ground velocity (lower than .05 m/s) are not high enough to cause induced effects in the city.

VULNERABILITY ASSESSMENT OF MONUMENTAL BUILDINGS

Vulnerability Assessment using the Vulnerability Index Method

The Catalogue of Historic and Artistic Heritage of Barcelona contains a total of 3400 buildings with the purpose of conserving the characteristic traits of each municipal district in the city. The catalogue divides the monuments in two levels of protection and only those included in level A of protection were considered for this study. The vulnerability analysis of the 68 monuments with a level A of protection was carried out using the vulnerability indexes for monumental typologies developed by Lagomarsino [7].

The 60 percent of the monuments were built during the XIX and XX centuries. The demolition of the old city walls in 1854 and the approval of Cerdá's urbanism expansion plan in 1859 promoted the construction business in Barcelona during the XIX and XX centuries. It is also interesting to note that the 34 percent of the monuments was constructed during the first half of the XX century. The 76 percent of all monuments considered belong to the palaces typology while the rest of monuments are classified as churches, monasteries, theatres, statues, castles and chapels.

The monuments were located on a geographical information system (GIS) in order to determine the level of intensity affecting then according to the deterministic scenario. The monuments GIS cover was crossed with the deterministic seismic hazard map with soil effects as shown in Figure 11 and the intensity affecting each monument was obtained.

Figure 12 shows the distribution of monuments according to the level of intensity expected to affect them. As can be seen 51 of the 68 monument are expected to experience an intensity of VII degrees.

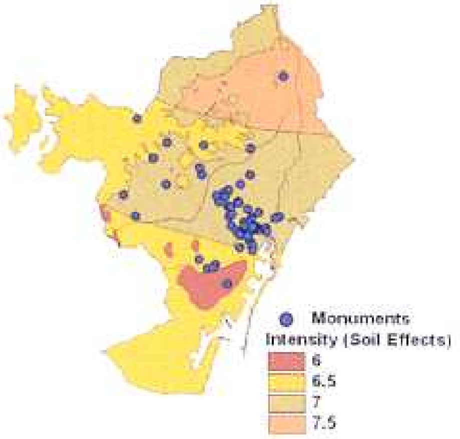


Figure 11 – Location of the monuments in the deterministic seismic hazard map.

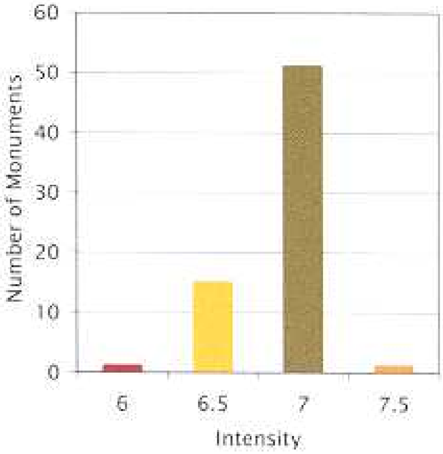


Figure 12 – Intensity level affecting the considered monuments.

Using the information gathered for all monuments, vulnerability indexes and vulnerability index modifiers were assigned to each monument as recommended by Lagomarsino [7] in order to obtain a vulnerability index adapted to the characteristic of each monument. Then the expected mean damage grade, μ_d, was calculated using the vulnerability function given by Lagomarsino [7]. The damage description associated to each damage grade is shown in Table 1.

Damage Grade	Damage Description
0	No damage
1	Negligible
2	Light
3	Medium
4	Severe
5	Collapse

Table 1– Damage grades qualitative description.

The mean damage grade was obtained for each monument using the lower, mean and upper vulnerability indexes. As expected churches, monasteries, chapels and theatres show the higher levels of mean damage grade. Maximum mean damage grades of 2, 3 and 4 were obtained using the lower, mean and upper vulnerability indexes, respectively. Figure 13 shows the 3 monuments with the highest values for the mean damage grade. Using the mean and lower values of the vulnerability index, some monuments obtained mean damage grades of 2 and close to 3, meaning that light to medium damages can be expected in their structures. Due to the nature of many monuments even minor damages can imply loosing their patrimonial value. Using the upper limits, the higher mean damage grades grow up to passed 4. Some monuments can even have a probability of collapsing due to their high mean damage grade. For example Sagrada Familia having the highest mean damage grade have a probability of collapsing, which although being small, can still come true.

It must be remembered that the mean damage grade represents a damage distribution and that damage probabilities must be calculated for each mean damage grade of each monument. Damage probability distributions for each monument using the lower, mean and upper values of the vulnerability indexes had been calculated using the binomial distribution (Lagomarsino [7]). The damage distributions for Sagrada Familia church are shown in Figure 14. As can be seen the upper values the collapse condition to be the most probable damage degree.

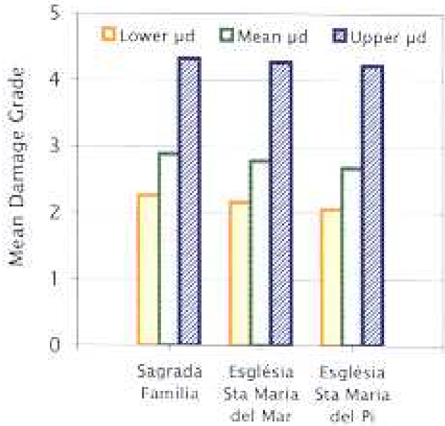


Figure 13 – Monuments with the highest mean damage grades.

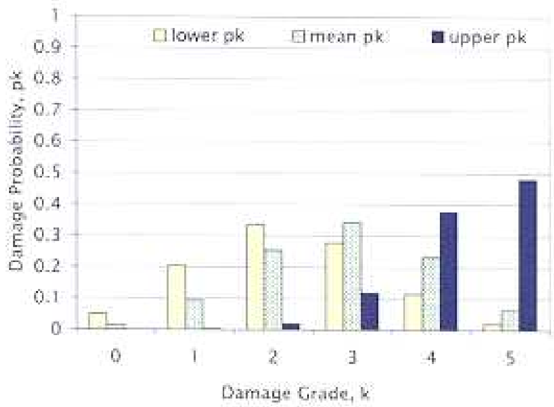


Figure 14 – Damage distribution for Sagrada Familia church.

Vulnerability Assessment using the Capacity Spectrum Method

The Santa María del Mar church and the Saló del Tinell were chosen as representative monuments to apply the capacity spectrum method. The gothic church of Santa Maria del Mar shown in Figure 15 was chosen as the representative church of Barcelona. From the palaces and mansions, the Saló del Tinell located within the aggregate of the Plaça del Rei was chosen as the other representative monument. It is also a gothic structure dating from the 14th century. Figure 16 shows a lateral and top view of the Saló del Tinell.

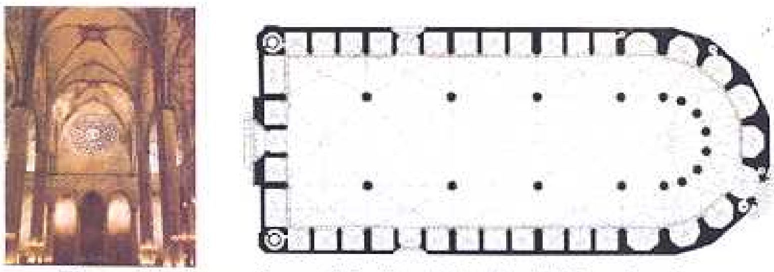


Figure 15 – Some views of the Santa Maria del Mar church.

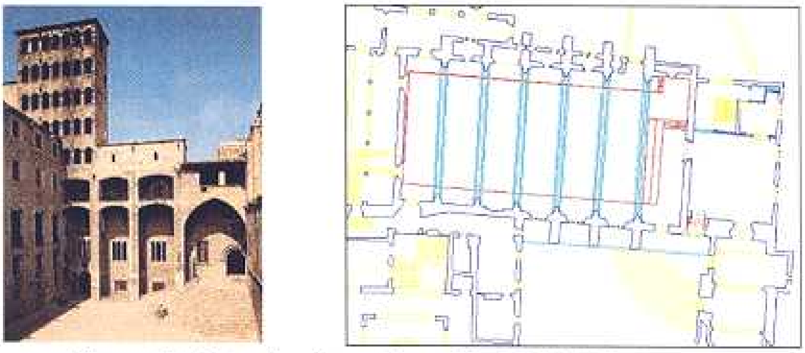
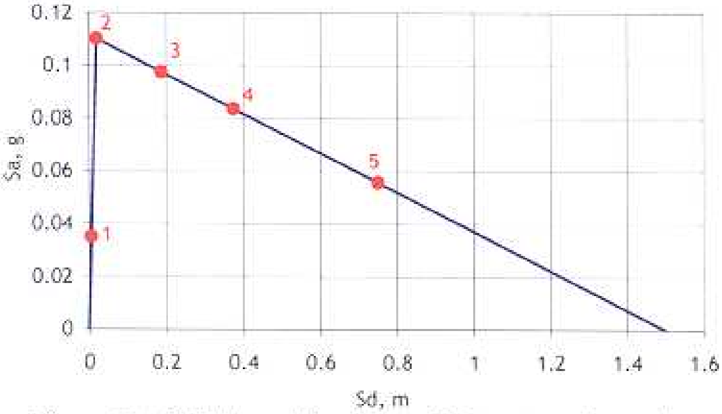


Figure 16 - Lateral and top views of the Saló del Tinell.

The capacity spectrum method compares the capacity spectrum of a structure with the demand spectrum from the seismic hazard in order to determine the performance of the structure under a given seismic hazard level. The seismic performance indicates how the structure behaves under seismic loading and provides the data needed to indicate the extension of the damage that can be expected in the structure. The capacity spectrum is a capacity curve of the structure expressed in terms of both spectral acceleration and displacement. The capacity curve for the Santa Maria del Mar church was obtained by Irizarry [8] using both finite element (FEM) analysis and equilibrium limit analysis, while the capacity curve for the Saló del Tinell is obtained using only the equilibrium limit analysis.

The capacity curve for the transversal response of Santa Maria del Mar church defined by Irizarry [8] using the results from the equilibrium limit analysis is shown in Figure 17. The expected spectral displacements are probably lower than 0.4 m, so the representative curve for the transversal response of Santa Maria del Mar church is limited up to a spectral displacement of 0.4 m. Irizarry [8] showed that the capacity curves obtained using the FEM and the equilibrium limit analysis present great similarity in the transition from the elastic to the non-linear phase. The damage limit states (Figure 17) were defined as fractions of S_u, the ultimate horizontal displacement of the centroid, as recommended by Lagomarsino [7]. The performance point of Santa Maria del Mar church was obtained using the procedure recommended by Milutinovic [9] for a bilinear representation of the capacity spectrum.



Damage Limit State	Damage Description
1	None
2	Slight
3	Moderate
4	Extensive
5	Collapse

Figure 17 – Definition of the damage limit states and capacity curve for Santa Maria del Mar.

The capacity curve for el Saló del Tinell was evaluated using only the equilibrium limit analysis. A minimum load factor of 0.21 was obtained for the structure model that includes the effect of the dependencies located beneath the Saló del Tinell. Figure 18 shows the capacity curve obtained for the Saló del Tinell and the damage state limits defined according to Lagomarsino [7].

The capacity curves obtained for the two representative monuments are shown in Figure 19. As can be seen the Saló del Tinell presents a greater resistance to lateral loads having a higher minimum load factor than the Santa Maria del Mar church. On the other hand the Santa Maria del Mar church exhibits a greater displacement capacity.

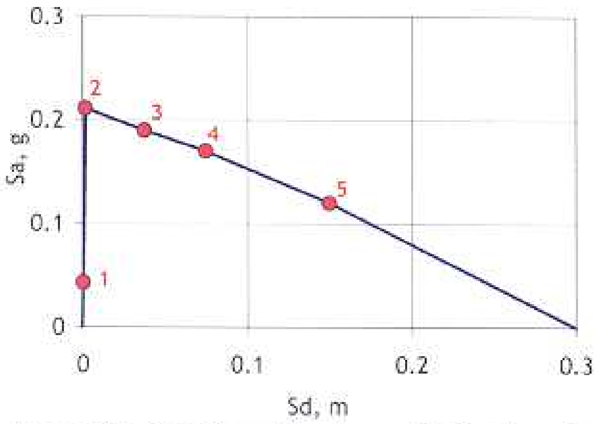


Figure 18 – Definition of the damage limit states and capacity curve for the Saló del Tinell.

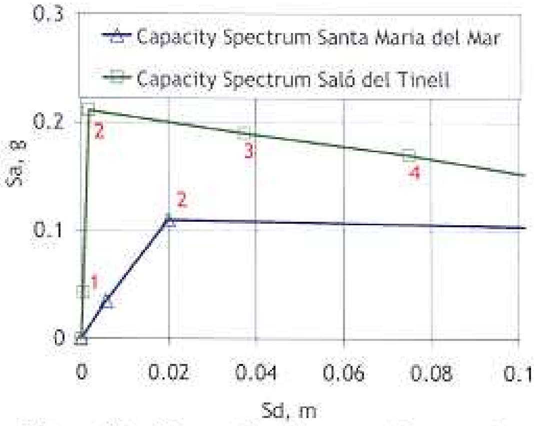


Figure 19 – Comparison between the capacity spectra for the two representative monuments.

Figure 20 shows the comparison between the capacity curve for the church and the probabilistic demand spectra for soil zone I. Notice that the performance point for each case is marked as a black dot. For both the probabilistic and deterministic demand, the performance point for the Santa María del Mar church lies within damage state limits for a slight damage condition.

Figure 21 presents the performance point obtained for the Saló del Tinell using the probabilistic demand spectra for zone II. For both the probabilistic and deterministic demand spectra, the performance points obtained show that the Saló del Tinell is expected to suffer slight damages for these scenarios. One must remember that in the case of monumental structure even slight damage can cause the loss of important cultural and historical heritage within the monuments structure.

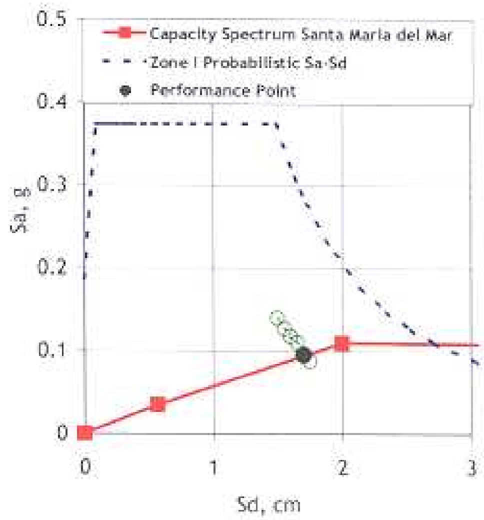


Figure 20 – Probabilistic performance point for the Santa Maria del Mar church.

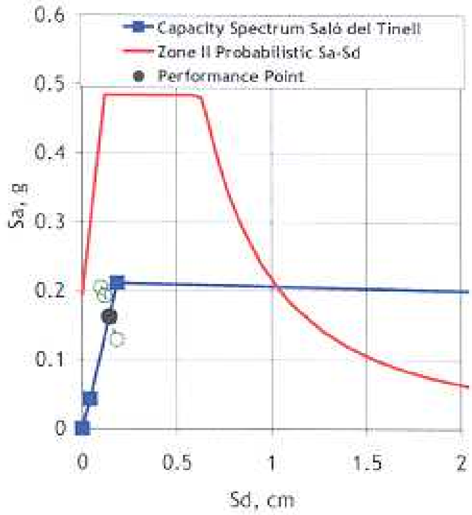


Figure 21 – Probabilistic performance point for the Saló del Tinell.

RESULTS

A seismic hazard assessment for the city of Barcelona and a damage assessment for the most important monuments were achieved using the methodologies defined within the RISK-UE project. The deterministic seismic hazard in terms of intensity agrees with the seismic hazard assessment performed by Secanell [2].

The deterministic acceleration response spectrum presents lower spectral acceleration values than the probabilistic acceleration response spectrum for a return period of 475 years. The spectral amplification factors for the spectral acceleration obtained in this study compare very well to those proposed by the Eurocode 8. Analytical forms for the acceleration response spectra and the corresponding demand spectra were defined to make easier the programming of the vulnerability assessment using the capacity spectrum method. No induced effects are expected in the city due to low levels of expected peak ground velocity and their absence in the historical earthquakes effect on the city.

The seismic damage evaluation for the most important monuments of Barcelona using the vulnerability index method revealed that churches are the most vulnerable monuments in the city. The maximum mean damage grade expected for Barcelona's monuments correspond to a condition of light to medium damages for the deterministic scenario. If the uncertainty of the vulnerability index is considered some monuments even have a high probability of collapse.

Applying the capacity spectrum method to the two representative monuments of the city the expected damage condition was evaluated using both the deterministic and the probabilistic demand spectra. A comparison of the capacity curves show that the Saló del Tinell has a higher lateral load resistance and a lower deformation capacity than the Santa María del Mar church. The performance points obtained for the two monuments correspond to a slight to moderate damage condition.

The damage conditions obtained using the two methods considered are quite similar for the two monuments. The only difference lies in the fact that the Santa Maria del Mar church does exhibit a small collapse probability even when the mean values of the vulnerability indexes are used. The damage conditions expected for the Santa Maria del Mar church are similar to the damages the church experienced during the historical earthquakes that had affected the city.

CONCLUSIONS

During the seismic hazard assessment for Barcelona city difficulties were found with the attenuation relationship used. Magnitude scale conversions were required to adjust Ambraseys [3] attenuation relationship to the acceleration levels observed in the Catalonian region. An attenuation relationship adapted to the region is needed to enhance the seismic hazard assessment of the area. The acceleration response spectra obtained for the city of Barcelona are higher in the short periods region than the acceleration response spectra recommended for the city by the Spanish seismic normative NCSE-02 [10] because the Spanish normative underestimates the contribution of earthquakes close to the city.

The vulnerability index method proves to be a rapid and useful method to evaluate the expected damage condition by making a simple survey of a group of buildings. The uncertainties in the vulnerability indexes proposed by Lagomarsino [7] cause a high dispersion in the mean damage grade values obtained for the most important monuments of the city.

The FEM analysis allows to model a structure in a more detailed way that others methods and to consider its non-linear behavior but can present problems for determining a convergent solution and the properties of the materials especially when old structures are considered. The equilibrium limit analysis allows evaluating with relative ease the collapse load of a structure but does not consider the deformability of the structure. The capacity spectrum method represents a useful method to evaluate the performance of a structure.

The methods exposed in this study had proved to be useful for the seismic risk assessment of monumental buildings. The mean damage grades obtained for the monuments show that light to medium damages are expected but in the case of monuments even minor damages can affect the cultural and historical value of a building. So measures should be taken to decrease the seismic vulnerability of these monuments.

ACKNOWLEDGMENTS

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