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# RISK ASSESSMENT OF REINFORCED CONCRETE BUILDINGS CONSIDERING THE EARTHQUAKE DIRECTIONALITY EFFECTS

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**Abstract.** *In order to assess the seismic risk of structures, several methods based on pushover analysis have been developed. These methods are very useful in the case of symmetric structures because they can be easily approximated by means of a 2D model. In the case of asymmetric structures several improvements to the pushover analysis procedure have been proposed for considering the effect of asymmetry on the global response. However, such methods, in some cases, can be more expensive, from computational point of view, than the nonlinear dynamic analysis. In this article, we propose to assess the effect of the directionality of the earthquake by using non-linear dynamic analysis and considering uncertainties in the mechanical properties of the materials and in the seismic action. We use as a case study a group of reinforced concrete buildings located in Lorca, Spain, damaged by the earthquake of May 2011. The results show a good agreement between the observed and the calculated damage.*

# 1 INTRODUCTION

In the seismic risk assessment of buildings are involved two main random variables, the vulnerability of the structure and the intensity of the seismic action. The uncertainty related to the former one depends on the mechanical properties of the materials, the weight supported by the structure or the participation of the non-structural elements, among others. The uncertainty of the second one depends on the fault mechanism and the soil conditions, among many others. Even if the seismic action is known, for instance in the case that the earthquake has occurred and an acceleration record is available, there is another source of uncertainty related to the directionality effect. It means that, due to topographical and geological conditions, among others, it is difficult to establish the incidence of the acceleration upon the buildings of the studied area. If data associated with the observed seismic damage are available, one can validate the computational method used for calculating the seismic damage. Several methodologies based on static procedures have been developed for assessing the expected seismic damage of buildings [1, 2, 3, 4, 5]. These methodologies are based on the assumption that the behaviour of the building is governed by the first mode of vibration. For tall or asymmetric buildings, further consideration should be made by taking into account the effects of higher modes in elevation [6, 7], in plan [8, 9, 10] or in both, plan and elevation [11, 12, 13, 14]. But, in some cases, due to the high irregularity of a building, it is very difficult to perform a reliable pushover analysis, which is the base of the procedures based on nonlinear static methods. In these cases, from our point of view, it is necessary to assess seismic damage by performing non-linear dynamic analysis (NLDA) instead of pushover analysis. However, ignoring particular cases, simplified static methodologies were applied in several previous studies in order to calculate the seismic risk of urban areas [15, 16, 17, 18, 19] obtaining successful results. In this article we propose to calculate the seismic damage of a group of buildings located in the San Fernando neighborhood of the city of Lorca, Spain, which was affected by the earthquake occurred in May 2011, by considering as numerical tool the NLDA. We include the uncertainties related to the mechanical properties of the materials and the directionality of the earthquake.

# 2 DESCRIPTION OF THE STUDIED BUILDING

In this article we calculate the expected seismic damage of a group of buildings located in the San Fernando neighborhood of the city of Lorca, Spain, after the earthquake in May 2011. These buildings have 5 stories, reinforced concrete structure, and are configured with columns and waffle slabs. Some of these buildings have been strongly affected by the earthquake. One important fact is that all the buildings have been built using the same structural blueprints. However, the difference between their damage levels was considerable: some of them were damaged beyond repair limit and others had no damage. A picture of one of these buildings can be seen in Figure 1. This figure also shows some damaged columns at the ground floor. . This fact can be explained if we consider the uncertainties associated with the mechanical properties of the materials and the effect of the directionality of the earthquake. In order to prepare the structural model, we have used the blueprints of the building which contains information not only on the geometry but also on the strength of the materials. Figure 2a shows a blueprint of the analyzed building. Figure 2b shows a plan view of the structural model used as a reference to define the angle of rotation in the calculations which have been carried out. From this figure, it can be concluded that the building is weaker in the *x* direction (the axes are indicated in the figure).

Figure 1: Buildings located in the San Fernando neighborhood of the city of Lorca, Spain, affected by the earthquake occurred on May 2011

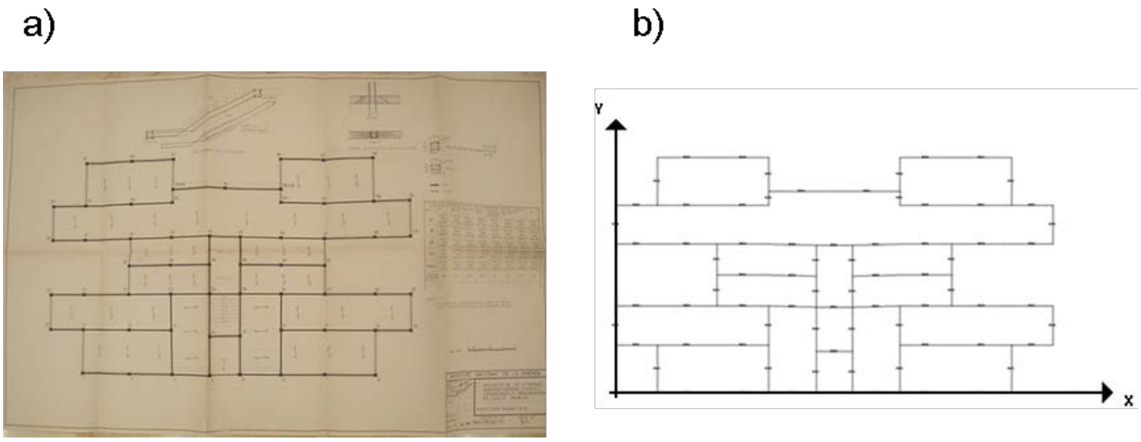


Figure 2: a) Blueprint of the building b) Plan view of the structural model

Figure 3 shows an aerial photo of the buildings of the San Fernando neighborhood, scored according to the damage caused by the earthquake. Green indicates that the building was not damaged; yellow indicates that the damage is reparable; and red shows that there is an imminent risk of collapse and, therefore, the building has been recommended for demolition. It is important to note that some buildings form aggregates up to 3 units, but the 2 units aggregate is the more common. . It can be seen that the buildings whose *x* axis makes an angle of approximately 20° or 200° with the EW component (using as reference the axes shown in Figure 2b) have a tendency to suffer less damage. The opposite happens with the buildings which make an angle with *x* axis of about 110° or 290°. However, the San Fernando neighborhood is located far away from the seismological station where the earthquake was recorded and, therefore, due to topographical and geological conditions, among others, it is difficult to determine the angle with which the record should be rotated according to the position of the neighborhood. For this reason, the seismic action is treated as a random variable whose source of uncertainty is due to the directionality.


Figure 3: Plan view of the buildings located in San Fernando neighborhood affected by the Lorca earthquake. Green indicates that the building was not damaged; yellow indicates that the damage is reparable; red indicates that there is an imminent risk of collapse

A 3D structural model used in the structural analysis of the buildings is shown in Figure 4. The software to perform the analyses was RUAUMOKO [20]. The modified Takeda model [21] was chosen among the hysteretic models available in the RUAUMOKO program to describe the mechanical behaviour of reinforced concrete. In order to define the yield surfaces of the material of the columns and beams, it was necessary to create interaction diagrams between the bending moment and the axial force, and between the bending moment and the angular deformation, respectively. The non-linear behaviour in shear has not been considered. Programs have been developed in MATLAB in order to calculate the yielding points necessary when defining the behaviour of the structural elements used in the dynamic analyses of the structures. The tangent-stiffness proportional Rayleigh damping model was used.

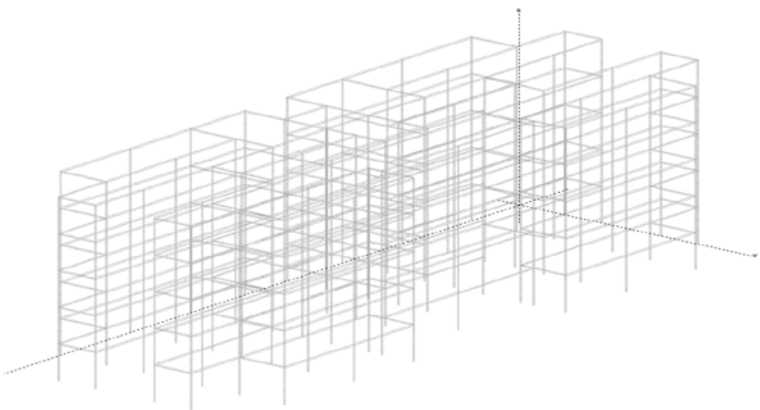

Figure 4: 3D structural model of the building

## 3 LORCA, MAY 2011 EARTHQUAKE

The magnitude of the Lorca earthquake was 5.1, that is, a moderated earthquake. But, this earthquake caused 9 casualties and great economic losses. This fact highlights the high seismic vulnerability of the buildings located in that area, but which is similar in other regions of Spain. The horizontal components of the earthquake are shown in Figure 5.

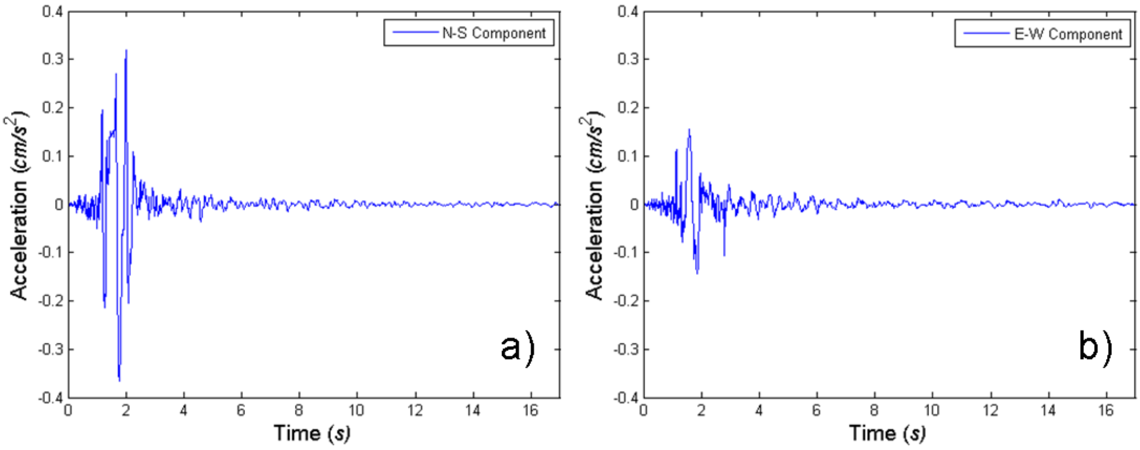


Figure 5: Horizontal components of the May 2011 Lorca earthquake

The uncertainties in the seismic hazard are considered by rotating the horizontal components of the record by an angle $\theta$ [22]

$$\begin{pmatrix} \ddot{u}_{x(\theta)}(t) \\ \ddot{u}_{y(\theta)}(t) \end{pmatrix} = \begin{bmatrix} \cos(\theta) & sen(\theta) \\ -sen(\theta) & \cos(\theta) \end{bmatrix} \begin{pmatrix} \ddot{u}_x(t) \\ \ddot{u}_y(t) \end{pmatrix} \tag{1}$$

where $a_{x(\theta)}(t)$ and $a_{y(\theta)}(t)$ are the horizontal components of the accelerogram when rotated anti-clockwise by an angle $\theta$, while $a_x(t)$ and $a_y(t)$ are the original components of the record. In order to consider the directionality effect, we rotated the horizontal components of the earthquake with an angle $\theta$ varying from 0° to 180° with increments of 1° and, then, for each angle, we calculated the response spectra of the rotated record $\ddot{u}_{x(\theta)}(t)$. Figure 6 shows the acceleration response spectra obtained after rotating the horizontal components. It can be seen that the variation in terms of spectral acceleration is very high in the range of the considered. It indicates that the seismic behavior of a building located in Lorca, when subjected to the Lorca earthquake, strongly depends on its azimuth. For this reason, it is necessary to include the directionality as a random variable in order to get reliable and accurate results. For instance, the fundamental period of the studied buildings is about 0.8 seconds and, for this value, the spectral accelerations vary from 0.072 *g* to 0.3748 *g*.

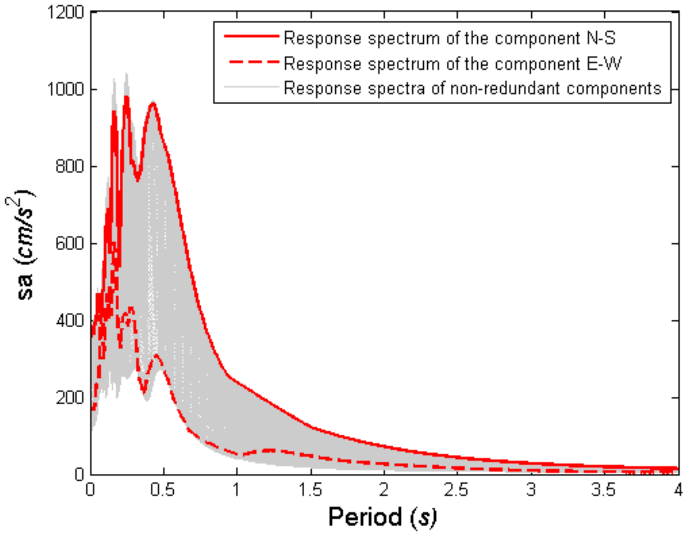


Figure 6: Acceleration response spectra obtained after rotating the acceleration record registered during Lorca earthquake

## 4 PROBABILISTIC NON-LINEAR DYNAMIC ANALYSIS

In the case of the studied building, the system of axes is given in Figure 2b. A series of nonlinear dynamic analysis has been performed considering not only the variation of the angle of incidence of the seismic action with the building but also the uncertainties associated to the mechanical properties of the materials. Thus, 3600 nonlinear dynamic analyses have been performed, in which the angle of rotation of the earthquake is treated as a random variable with a uniform probability distribution in the interval (0°, 180°). The compressive strength of concrete, *fc*, and the tensile strength of steel, *fy*, are also considered as random variables, following a Gaussian probability distribution whose characteristics are shown in Table 1. These values are taken from the original blueprints. The spatial variability of these variables has been also considered as shown by Vargas et al. [23].

| Variable | $\mu_x$ $(kPa)$ | $\sigma_x$ $(kPa)$ |
|---|---|---|
| *fc* | 21000 | 2100 |
| *fy* | 500000 | 50000 |

Table 1: Statistical moments of the mechanical properties of the materials considered herein

It can be expected that the seismic damage depends strongly on the angle of rotation and that even the effect of the uncertainties associated with the materials properties could be negligible. After performing the dynamic analysis, we calculated the damage index of Park and Ang [24]

$$DI_{\mathrm{E}} = \frac{\mu_m}{\mu_u} + \frac{\beta E_h}{F_y \mu_u \delta_y} \tag{2}$$

where $\mu_m$ and $\mu_u$ are the maximum and ultimate ductilities, respectively, and the subscript E stays for the element level damage index; $\beta$ is a non-negative parameter which considers the effect of cyclic loading on the structural damage; $E_h$ is the dissipated hysteretic energy; $F_y$ is the yield load; and $\delta_y$ is the yield displacement. The global damage index of the structure, *DI*, is a weighted mean of the element damages, in which the weights are the ratio of the hysteretic energy dissipated by each element to the total hysteretic energy dissipated by the structure:

$$DI = \sum_i \lambda_i DI_{\mathrm{E}} \tag{3}$$

In this equation, *DI* is the dynamic analysis based global damage index of the structure, $\lambda_i$ is the ratio of the dissipated hysteretic energy of an element E to the dissipated hysteretic energy of the entire structure. Vargas et al. [25] have used the damage index of Park and Ang to get damage curves by considering uncertainties. Figure 5 shows the variation of damage as a function of the incidence angle of the action and also shows the uncertainty associated with the mechanical properties of materials. To evaluate the distribution of damage, it is convenient to group the results shown in Figure 5 in the histogram shown in Figure 6.

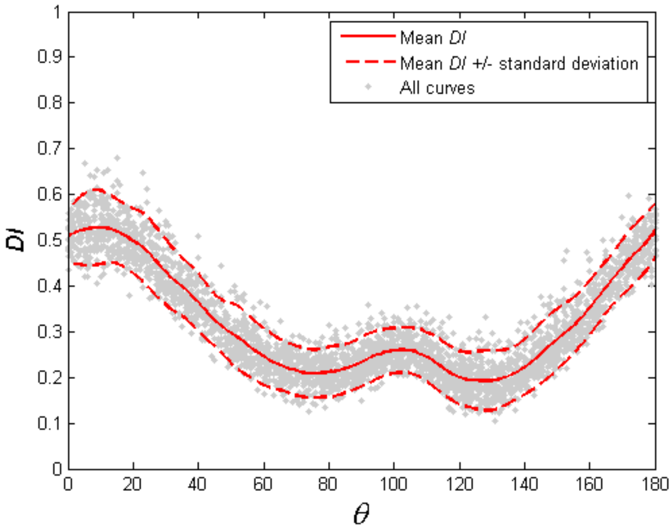


Figure 5: Variation of the damage index considering the angle of rotation of the earthquake and the uncertainties associated with the mechanical properties of materials

This histogram shows that the resultant distribution function has a bimodal shape. This is due to the fact that the expected damage, when the seismic action is maximum in the *y* direction, is greater than when the seismic action is maximum in the *x* direction. This may explain why some buildings suffered more damage in one direction than the others. On the other hand, Park et al. [26] assigned a qualitative description of the damage depending on the calculated value of the damage index. For example, they state that, if the damage index of a building is greater than 0.4, the repair cost exceeds the construction cost of the building; for lower damage repair is economically viable. If the calculated damage index is less than 0.2, Park et al [26] consider that damage is slight, corresponding to '*sporadic occurrence of cracking*'. These thresholds are important in the analysis of the results because, as is shown in Figure 3, some buildings were not damaged and others were recommended for demolition. If we analyze the histogram of Figure 6 according to the limits of damage described previously (see the red lines) we can establish the percentages of buildings that suffer slight, moderate and extensive damage, assuming that extensive damage is not repairable and, therefore, the building should be demolished. This can be done by counting the number of samples contained in each interval. This count shows that 511 samples presents a $DI$<0.2, 2109 samples are in the range 0.2>$DI$<0.4 and for 980 samples $DI$>0.4. Whereas the number of samples is 3600, the probabilities of occurrence of each damage state are 14.19%, 58.86% and 26.95% for slight, moderate and extensive damage, respectively. The damage observed indicated that 13.33% of the buildings had damage slight, 60% had moderate damage and 26.67% had extensive damage, for these last cases, demolition was recommended.

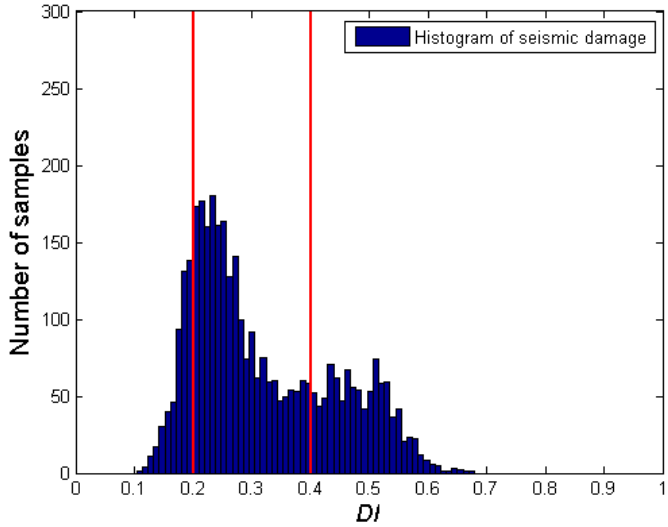


Figure 6: Histogram of the expected damage of Park and Ang

These results are plotted in the histogram shown in Figure 7 in which a good agreement between calculated and observed damage can be appreciated which highlights the importance of considering the uncertainties in the risk and vulnerability analysis of structures.

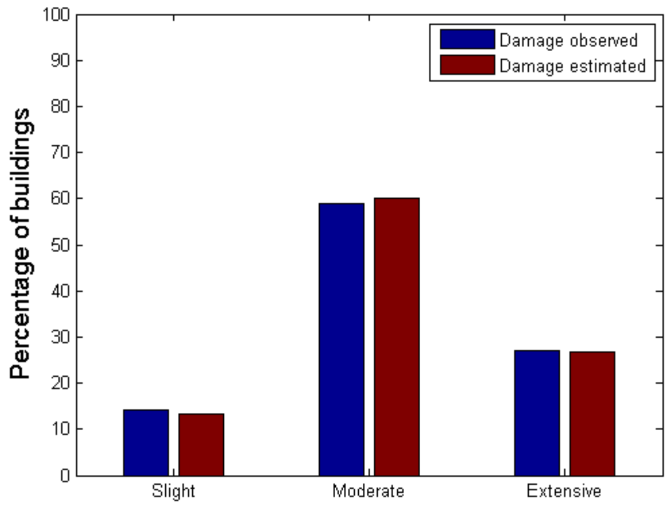


Figure 7: Comparison of observed and calculated damage

It is complicated to establish, from the available data, which is the angle at which the acceleration record should be rotated to simulate the acceleration occurred in the San Fernando neighborhood. Figure 5 shows the specific damage distributions for any angle of rotation, reducing uncertainty. That is, if damage probability distributions are analyzed for two orthogonal angles, e.g. 40° and 130°, we obtain the probability density functions shown in Figure 8.

The principal moments of these probability density functions are shown in Table 2. It might be supposed that 40° coincides with the more damaged direction and 130° coincides with the less damaged direction. Note that this assumption could explain quite well the variation between the observed damage. However, this is a hypothesis and the theoretical basis on which it is established is beyond the scope of this paper.

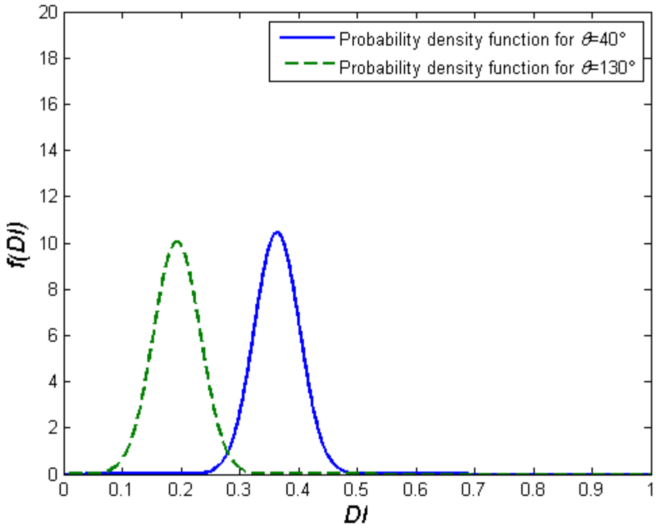


Figure 8: Probability density functions of damage for $\theta = 40°$ and $\theta = 130°$

| $\theta°$ | $\mu_{ID}$ | $\sigma_{ID}$ |
|---|---|---|
| 40° | 0.3634 | 0.0382 |
| 130° | 0.1930 | 0.0397 |

Table 2: Statistical moments of damage for $\theta = 40°$ and $\theta = 130°$

## 5 CONCLUSIONS

This article shows how the methodology of seismic risk assessment based on the nonlinear dynamic analysis considering uncertainties, is an excellent alternative for studying the directionality effect of the seismic action on asymmetric buildings. We modeled the expected seismic damage of a group of buildings affected by an earthquake occurred in May 2011 in Lorca, Spain. Thus, the objective was to assess the damage in buildings due to a specific action and it was not been necessary to consider the uncertainties due to the earthquake-to-earthquake variation. The computational cost to obtain the results presented in this paper is relatively high. However, the results are in good correspondence with the observed damage. Due to the treatment of the uncertainties related to the seismic action and to the mechanical properties of the materials, the results obtained in this article can be extended for assessing the behavior of others buildings of similar typology affected by the earthquake of Lorca. It is important to note that, if the angle with which the acceleration record should be rotated in order to simulate its effect in a given area is known, the results obtained can be extended to predict the distribution of the seismic damage with less uncertainty.

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