SEISMIC DEMANDS AS A RESULT OF DIRECTIVITY EFFECTS FROM THE Mw 5.1 2011 LORCA (SPAIN) EARTHQUAKE

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ABSTRACT

The May 11th 2011, Lorca earthquake in Southeastern Spain was a damaging event, especially considering its relatively low magnitude (Mw 5.1), which produced 9 fatalities, more than 300 injuries, and more than 462 million Euros in economic loses. Recorded ground motions and corresponding spectral ordinates significantly exceed those in current Spanish probabilistic seismic hazard models, as well as those in the Eurocode and Spanish building codes. A pulse directivity effect has been postulated by several investigators to explain these differences, the objective of this paper is to assess such effects on ground motions recorded at the LOR station during the 2011 Lorca earthquake, and to evaluate the significance of these effects on earthquake resistant design in moderate seismic regions. First, we studied the likelihood of the presence of a directivity pulse, by comparing different parameters of the recorded ground motions to analytical pulses. Additionally, we present a novel technique to extract directivity pulse features, based on the match of the response spectrum of a simple analytical pulse and the spectrum of the recorded ground motion. In a second part, we relate the inelastic displacement spectra to some models that try to capture the displacement demand features of earthquakes presenting directivity-pulse characteristics. We conclude that a large part of the impact caused by this relatively small earthquake owes to directivity effects, an aspect which is typically ignored, both in probabilistic seismic hazard analysis and in most building codes.

Keywords: Directivity; Directionality; Near-Fault; Pulse-Like Ground Motions; Inelastic Spectra

1. INTRODUCTION

The Lorca, May 11th 2011, earthquake in South-Eastern Spain was a damaging event, especially considering its relatively low magnitude Mw 5.1 (Lopez-Comino et al, 2012) (Cabañas et al., 2013). The earthquake lead to a death-toll of 9 people, more than 300 people injured, and approximately €462 M in direct economic losses (Alvarez-Cabal et al., 2014). Damages included the collapse of a 4-story modern reinforced concrete building (Fig 1a) and the partial collapse of an 18th century church (Fig. 1b), along with extended damages in nonstructural elements.

Figure 1. (a) Collapsed modern reinforced concrete building. (b) Partial collapse of the Santiago Church, a masonry building dating from the XVIII century (from Cabañas-Rodriguez et al., 2011)

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The focal mechanism solution corresponds to a reverse and strike-strike slip faulting mechanism with a very shallow crustal depth of approximately 3 km (Cabañas-Rodriguez et al., 2011), to 4 km (Martínez-Solares et al., 2012). The maximum PGA in the event, which was recorded at the Lorca station, was 0.37·g in the N30W component and is more than three times larger than the one specified in the Spanish code for this region (based on a 10% probability of exceedance in 50 years) being also the largest peak ground acceleration ever recorded in Spain (Cabañas et al., 2013) (Moratto et al., 2014). A possible induced origin for this earthquake, related to groundwater crustal unloading, has been pointed as a cause by some researchers (González et al. 2012). However, the study presented in this paper does not address the specific causes (natural or induced stress build-up) that may have led to the earthquake triggering.

It is well known that rupture directivity effects can lead to strong pulse-like ground motions (Bertero et al., 1978), (Anderson and Bertero, 1987), (Hall et al., 1995), (Iwan, 1998), (Alavi and Krawinkler, 2001). The propagation of fault rupture toward a site, at a velocity close to the shear wave velocity, causes most of the seismic energy from the rupture to arrive in the form of a single large pulse of motion that occurs early in the seismic record (Somerville et al., 1997). Furthermore, the radiation pattern of the shear dislocation on the fault causes these large pulse-like ground motions that tend to be oriented in the direction perpendicular to the fault plane, leading to more intense ground motions in the normal component than in the parallel component.

Although near-fault pulse-like records have been included in the development of conventional ground motion prediction models (GMPE), they do not properly account for directivity effects because most of them are aimed at predicting the geometric median of the intensity of the two horizontal components, therefore systematically underestimating the intensity of ground motions affected by directivity in the maximum direction, which is typically the fault-normal component. Furthermore, the standard deviation of most ground motion prediction models is averaged over all distances leading to underestimation of the dispersion, especially near the fault (Abrahamson, 2000). Some more recent GMPM have explicitly incorporated directivity effects (e.g. Somerville et al., 1997) but modifications are only introduced for events with magnitudes larger than 6.5. Recently, such directivity effects have been observed in earthquakes with magnitudes between 6.0 and 6.5 such as the 2004 Mw 6.0 Parkfield, earthquake (Shakal et al., 2005), the 2009 L’Aquila Mw 6.3 earthquake (Chioccarelli and Iervolino, 2010) or the 2011 Mw 6.3 Christchurch earthquake (Bradley et al., 2014), pointing out that these damaging pulse-like ground motions can occur in earthquakes with magnitudes smaller than 6.5.

Several researchers (Lopez-Comino, 2012) (Rueda-Nunez et al., 2012) (Rueda-Nunez, 2014) (Alguacil et al., 2014) (Pro et al., 2014) have conjectured the presence of a directivity pulse in the 2011 Lorca earthquake despite its relative small magnitude. The objective of this paper is to evaluate directivity effects on ground motions recorded during the 2011 Lorca earthquake, and to evaluate the significance of these effects on earthquake resistant design in moderate seismic regions. In the first part of this paper, we study the likelihood of the presence of that pulse, by conducting a comparison of different parameters of recorded ground motions to analytical pulses. In the second part of the paper, we relate the recorded ground motion and its inelastic displacement spectra to some of the most recent statistical models that try to capture the displacement demand features of earthquakes presenting directivity-pulse characteristics.

2. LORCA 2011 EARTHQUAKE GROUND MOTION DATA

The accelerograph station in the city of Lorca recorded two horizontal ground motion signals in the N30W and N60E directions (Fig. 2a), which roughly match the fault-normal and fault-parallel directions of the causative Alhama de Murcia Fault (AMF). The corresponding elastic pseudo-acceleration spectra and their geometric mean are shown in Fig. 2b. It can be seen that spectral ordinates in the fault-normal direction over a wide range of periods are more than twice than those in the fault-parallel direction. This figure clearly illustrates how, if one were to design based on the geometric mean, one would significantly underestimate the intensity of the motion in the fault-normal direction and overestimate the motion in the fault-parallel direction.
Several researchers (Martínez-Díaz et al. 2012) (Rueda et al., 2014) have been able to determine the approximate slip distribution of the fault area of rupture indicating that the rupture propagated from the hypocenter to an upward-southwest direction in a strike-reverse mechanism, toward the city of Lorca where the recording station is located. The Joyner and Boore distance is approximately R_{jb}=1.26 km, and no hanging-wall amplification effect is expected in the recorded ground motion, given that the recording site lies on the footwall side of the surface projection of the top edge of rupture.

According to the Spanish Earthquake-Resistant Building Code site classification, the recording site is located on a Class II, (Blazquez-Martinez et al., 2014), corresponding to medium to soft rock, with shear wave velocity $400 \leq V_{s,30} \leq 750$ m/s. For the rest of the analysis, the site has been considered to have $V_{s,30} = 575$ m/s corresponding to the average of the upper and lower boundaries of site class II.

### 3. LORCA 2011 EARTHQUAKE NEAR-FAULT PULSE-LIKE GROUND MOTION

Following the methodology proposed by Shahi and Baker (2013) to search for pulse-like patterns in earthquake ground motions and extract its prominent features (pulse period and pulse velocity and acceleration components), based on a wavelet decomposition of the ground velocity time-history, it was found that a distinct pulse feature dominated the ground motion recordings (Fig. 3b). The extracted pulse signal shows a pulse period $T_p=0.48s$, a result identical to that obtained by (Rueda, 2014) when applying the algorithm by Baker (2007).
Additionally to the method proposed by Shahi and Baker (2013), which is based on the use of the Daubechies 4 wavelet (Db4), a similar pulse extraction was performed using the Mavroeidis and Papageorgiou (2003) wavelet (M&P). The M&P wavelet is a modification to the Gabor wavelet, except that instead of having a Gaussian time modulation it has a harmonic modulation facilitating closed-form solutions to oscillators subjected to this pulse. This wavelet, has the advantage of being defined by a small number of input parameters which have an unambiguous physical meaning. The parameter $T_p$ controls the period of the pulse, $A$ controls the amplitude of the harmonic, while $\gamma$ controls the width/duration of the modulating function which, together with $T_p$ control the number of zero crossings in the wavelet, and finally the parameter $\nu$ defines the phase of the amplitude-modulated harmonic. The results of this M&P wavelet pulse extraction show a pulse similar in shape and coincident in time with the previous one, although with a pulse period somewhat larger of $T_p=0.62s$. The other M&P wavelet parameters were found to be $\gamma=2$ and $\nu=0$ (Fig. 3b).

Besides these two pulse-feature extraction methods based on the comparison between the ground motion record and the analytic pulse in the time domain, a different approach based on the comparison of the response spectra was used. In this complementary approach, the parameters are selected to minimize the differences between the pseudo-velocity response spectrum of the earthquake record and the pseudo-velocity response spectrum of an M&P analytic pulse as modified by Alonso and Miranda (Alonso-Rodriguez and Miranda, 2015). The likely pulse parameters are found by performing a least-squares fit between both spectra. With this approach, the most likely M&P pulse parameters were found to be $A_p=0.041\cdot g$, $f_p=1.49$ Hz, $g_p=1.00$, $a=0.18$ (Fig. 4).

Table 1 summarizes the period values obtained by each extraction methodology. The differences in period, which can be attributed to the uncertainty intrinsic to each methodology, become relevant when assessing the significance of the pulse in terms of the intended intensity measure: if this were a response spectrum, the spectrum match would provide a better fit.

Table 1

<table>
<thead>
<tr>
<th>Spect. Acceleration $S_a$ [g]</th>
<th>Spect. Velocity $S_v$ [cm/s]</th>
<th>Acceleration $a_g$ [g]</th>
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Figure 4. (a) Pseudo-acceleration 5% damped spectra for the N30W component, and for the M&P wavelet with pulse parameters that match the pseudo-velocity spectrum. (b) Pseudo-velocity spectra for the fault-normal component, and for the M&P wavelet. (c) Acceleration record of the fault-normal component and of the velocity-spectrum fitted pulse.
Figure 5. (a) Fault-Normal record component, where intervals 1 and 2 show significant zero-crossings of the pulse. (b) Normalized cumulative squared velocity for the fault-normal component and the M&P pulse, where intervals 1 and 2 corresponding to zero-crossings amount 79% of the CSV.

Once that the residual ground motion has been extracted, the cumulative squared velocity (CSV) was computed, in order to apply the criterion by Baker (2007) and to identify if the build-up of pulse energy arrived before than a large build-up of the original signal energy occurs. The limits of obtaining a 10% of the CSV in the extracted pulse before obtaining a 20% of the CSV in the original ground motion are satisfied, as can be appreciated in Fig. 5.b for the M&P pulse.

Table 1. List of pulse periods obtained with each extraction method.

<table>
<thead>
<tr>
<th>Extraction Method</th>
<th>Pulse Period $T_p$ [s]</th>
<th>$T_p/T_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelet Db4</td>
<td>0.48</td>
<td>1.10</td>
</tr>
<tr>
<td>Wavelet M&amp;P</td>
<td>0.62</td>
<td>0.85</td>
</tr>
<tr>
<td>Velocity Spectrum Match</td>
<td>0.67</td>
<td>0.79</td>
</tr>
</tbody>
</table>

The zero-crossings of the significant pulse are shown in intervals 1 and 2 of Fig 5a, while Fig 5b shows the contribution to the cumulative squared velocity (CSV) for this interval totaling a 79% of the CSV, along with the corresponding CSV for the extracted pulse. Comparing the previous results, we can observe a very good fit both for the $M_w-T_p$ relationship obtained by Shahi and Baker (2013) for the pulse-like records in the NGA West2 database, as well as for the Mavroeidis and Papageorgiou (2003) expression for their ground motion catalogue (Fig 7a).

Figure 6. (a) Elastic pseudo-acceleration 5% damped spectra for the fault-normal component, and Db4 and M&P pulses (b) Elastic pseudo-velocity spectra for the fault-normal component, and Db4 and M&P pulses.
Figure 7. (a) Pulse period versus earthquake magnitude for the NGA-West2 database records containing a pulse, the M&P database and Lorca 2011 earthquake, plotted along with (the Shahi and Baker, 2011) and (Mavroeidis and Papageorgiou, 2003) expressions for pulse-period expectation. (b) Spectral acceleration amplification factor $A_f$ due to directivity pulse (Shahi and Baker, 2011), and pulse to residual ratios for each wavelet.

Shahi and Baker (2013) proposed a local amplification factor $A_f = S_\text{pulse}/S_\text{residual}$ which amplifies spectral ordinates in the neighborhood of the pulse period. For this purpose, they adopted the functional form previously proposed by Ruiz-Garcia and Miranda (2005). This amplification factor is plotted in Fig. 7b for the Lorca pulse and residual motions, along with the Shahi and Baker expression, which captures well the main characteristic of the pulse, although the Lorca earthquake is somewhat larger.

4. LORCA 2011 EARTHQUAKE FORWARD DIRECTIONALITY

The difference in terms of spectral acceleration that can be present in a given pair of orthogonal ground motion records of the same event, and their relation to the spectral acceleration predicted by some GMPE model, has been pointed out by different authors (e.g., Baker and Cornell, 2006; Boore, 2010). The usual intensity measure of many attenuation models is the geometric mean of two spectral ordinates computed from as-recorded orthogonal records. This geometric mean value can depart significantly from the spectral acceleration in an orientation where a maximum would occur, especially in those cases where large polarization of the ground motion can be present. Boore (2010) developed direction-independent measures spectral ordinates. $S_{\text{RotD}50}$ corresponds to the median of spectral ordinates at all possible orientations, while $S_{\text{RotD}100}$ and $S_{\text{RotD}00}$ are intensity measures that provide information on what the maximum and minimum spectral acceleration are in any possible direction, respectively. Fig. 8 shows polarization plots of the Lorca 2011 earthquake for three chosen periods, one being the pulse period $T_p=0.48s$, where the magenta discontinuous line shows spectral acceleration amplitude at any given direction for that particular period.

Figure 8. Normalized displacement polarization plots, where $\Delta_{\text{rot}}$ is the elastic displacement response and $\Delta_{\text{max}}$ is the maximum displacement in each direction for a SDOF oscillator with vibration period of (a) $T=0.20s$, showing maximum polarization at an angle fairly close to the fault-normal direction (N30W recorded ground motion). (b) $T=0.48s$, the pulse period, showing maximum polarization at an angle 30º East of fault-normal direction. (c) $T=1.00s$, showing maximum polarization at an angle 25º East of fault-normal direction.
5. LORCA 2011 EARTHQUAKE AS PREDICTED BY NGA-WEST2 GMPE

Shai and Baker (2011, 2014) proposed a statistical model to take into account both the polarization and pulse directivity effects (directionality and forward-directivity), departing from the Boore and Atkinson (2008) GMPE (B&A) and including adjusting terms. Figure 13 shows the results computed for a reverse-slip fault mechanism earthquake, $M_w = 5.1$, Joyner and Boore distance $R_{jb} = 1.26\text{km}$, and a $V_{s,30} = 575\text{m/s}$, which likely correspond to the characteristics of the recorded ground motion at the Lorca accelerometer. The graphs shown in Figure 10 correspond to the B&A GMPE without any directionality or directivity adjustments, with each of these adjustments, and with both adjustments. From Figure 10 we can note that, although the value of PGA and spectral ordinates for very short periods (e.g. between 0 and 0.2 s) show differences from the expected median value, these still fall within the uncertainty range of this particular GMPE. However, the results show how the recorded N30W ground motion departs significantly from the B&A 2008 GMPE, with many spectral ordinates (e.g., between 0.2 and 0.8s) being more than two standard deviations above the median values, and how the adjustments proposed by Shahi and Baker present reasonably good agreement with the recorded ground motion if both directionality and directivity are taken into account.
Figure 10. (a) Boore and Atkinson (2008) 5% damped median spectral acceleration and ±σ intervals. Response spectra for the Lorca N30W component, (b) The Shahi and Baker (2014) modified model of spectral acceleration to the B&A (2008) model, considering the amplification due to directionality of the strongest component, (c) The Shahi and Baker (2011) modified model, considering the amplification due to the near-fault forward directivity pulse. (d) The Shahi and Baker (2011, 2014) modified for both directionality and directivity pulse

Some other nearby stations records (in particular AM2, MUL, ZAR, VLR, OLU, and VER, in a distance range of 30 km to 50 km), and corresponding response spectra, have been carefully examined in the same terms as for the LOR station. Unfortunately, and as indicated by Moratto et al. (2014), the location of all other stations are much farther away from the source which, in combination with the rather small magnitude of this event, make the study of possible directivity effects at the other stations far more difficult. In this sense, for these other stations a clear pulse signature has not been found as for the LOR station case.

6. LORCA 2011 EARTHQUAKE INELASTIC SPECTRA

Baez and Miranda (2000) showed that modifying the elastic spectral ordinates to take into account directivity effects in near-fault pulse-like ground motions was not enough because most structures are not designed to remain elastic and because the ratio of inelastic to elastic spectral ordinates of these types of ground motions can differ from those recorded away from the rupture. Various authors (e.g., Baez and Miranda 2000, Akkar et al. 2004; Ruiz-Garcia and Miranda 2005; Ruiz-Garcia 2011; Iervolino et al. 2012) have proposed expressions for describing inelastic to elastic displacement ratios for near-fault pulse-like ground motions. Figure 11 shows the displacement time-histories corresponding to systems with periods ranging from 0.01s to 2.00s, force reduction factors (R=1, 2, 4, 5, 6), and a post-yield stiffness ratio of 3% for the Lorca 2011 N30W component for different period ratios T/T_p (short period range, pulse period range, and long period range). In all cases, the displacement time-histories seem dominated by a large abrupt inelastic displacement increment soon after the 6s mark, rather than a steady increase in inelastic displacement produced by consecutive pulses.
Ruiz-García and Miranda (2003) proposed estimating the ratio of inelastic to elastic spectral ordinates with an expression, which formed the basis of the simplified expression (1) included in ASCE 41-06, where $R$ is the ratio of lateral strength required to maintain the system elastic to the lateral strength of the structure, $T$ is the fundamental period of vibration of the structure, and $a$ is a parameter that depends on site conditions.

$$C_{R} = 1 + (R - 1) \cdot \left[ \frac{1}{a T^2} \right]$$

Ruiz-García and Miranda (2005); Ruiz-García, (2011), proposed modifications to the previous equation to estimate inelastic displacements of structures near major faults as follows:

$$C_{R} = \frac{\Delta_{inelast,R}}{\Delta_{elast}}$$
\[ C_R = 1 + (R - 1) \cdot \left[ \frac{1}{\eta_0^\prime(T/T_p)} \right] + \theta_2 \cdot \left( \frac{T_p}{T} \right) \cdot \exp \left( \theta_3 \cdot \left( \ln \left( \frac{T}{T_p} - 0.08 \right) \right)^2 \right) \]

(2)

Similarly, Iervolino et al. (2012) proposed a similar functional form as a function of the period normalized to the pulse period \( T/T_p \) but added an extra term to capture that local maximum in displacement demand. All the four expressions (ASCE/SEI 2007, Ruiz-García and Miranda 2003, Ruiz-García 2011, and Iervolino et al. 2012) have been evaluated (with values \( T_g=0.56 \text{s} \), and \( T_p=0.48 \text{s} \)) for force reduction factors of \( R=[4, 6] \), and then compared to the inelastic to elastic displacement ratios \( C_R \) obtained for the Lorca 2011 earthquake. The apparent trends show that the Lorca 2011 earthquake presented larger inelastic displacements than what could be expected at all range of periods and force reduction factors for the Iervolino et al. (2012) expression (in the order of \( +\sigma \)), while the Ruiz-García and Miranda (2005) expression shows a better fit in predicting the inelastic displacements. The Ruiz-García and Miranda, (2005) and Ruiz-García (2011) expression shows a more conservative trend, predicting larger displacements than observed for \( T \geq 0.25 \text{s} \). However none of the aforementioned expressions is able to capture the large local maxima occurring at \( T=0.20 \text{s} \), or conversely \( T/T_p=0.40 \).

7. CONCLUSIONS

The Lorca, May 11th 2011, earthquake recorded ground motions have been analyzed both in terms of spectral accelerations and inelastic displacement spectra. Response spectra ordinates were significantly larger than those expected using probabilistic seismic hazard analyses, and those specified in the Spanish building code and the Eurocode. We conclude that these unexpectedly large accelerations were caused by a strong forward-directivity pulse with a period close to \( T_p=0.6 \text{s} \). This finding has important consequences for earthquake resistant design because directivity effects are currently not explicitly addressed in most seismic codes. Furthermore, this earthquake illustrates that important directivity effects can occur even in \( M_w \leq 5.1 \) events.

Analyses conducted in this study show that two relatively simple wavelets are capable of reproducing the main features of the time series of the fault-normal component of the recorded ground motions as well as the main characteristics of response spectral ordinates. Furthermore, modifications recently proposed for considering directionality and directivity effects based on NGA2 ground motions, despite currently being recommended only for seismic events with \( M_w \geq 6.0 \), together with expressions of inelastic displacements ratios specific for near-fault pulse-like ground motions, if they are applied to these smaller magnitude events, are capable of capturing the main features of both elastic and inelastic spectra of the motion recorded in the fault-normal direction.

8. REFERENCES


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