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A review on oriented fall structures (Earthquake Archaeological Effect, EAE) induced by instrumental earthquakes

Análisis de caídas orientadas de estructuras (efecto arqueológico de terremotos) inducidas por terremotos instrumentales

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Abstract

Oriented fallen structures (e.g. columns, obelisks) at archaeological sites have been used as an indicator of seismic damage. However, their interpretation is controversial, especially in relation to the influence of the intrinsic features of the structures on the recorded damage (e.g. orientation, construction quality, conservation). In this paper we analyze oriented fallen structures associated with three instrumental seismic series, with intensities ≥ VII EMS: Lorca earthquake, Spain (05/11/ 2011); Christchurch seismic sequences, New Zealand (09/04/2010 and 02/22/2011) and Emilia Romagna Earthquakes, Italy (05/20/2012 and 05/29/2012). Quantitative data obtained in this study reveal the consistency of the orientations of the collapsed structures in relation to the epicenter locations, regardless of their age, type and conservation degree. Seismic shocks related to near-field earthquakes seem to produce falls with consistent orientations in relation with dominant directionality of ground motion. Nonetheless, in the case of archaeological sites other possible causes have to be considered to assess the possible seismic origin of the damaged structures.

Key words: earthquake archaeological effects (EAEs); oriented fall structures; Christchurch earthquakes; Lorca earthquake; Emilia Romagna earthquakes**.**

Resumen

Las caídas orientadas de estructuras en yacimientos arqueológicos (e.g. columnas, obeliscos) se han utilizado como indicadores de actividad sísmica. Sin embargo, su interpretación ha sido siempre controvertida, especialmente con respecto a la influencia de las características de las estructuras en los daños que registran (calidad de la construcción, conservación, etc.) en relación a la orientación de colapso. En este trabajo se analizan las caídas orientadas de estructuras asociadas a tres series sísmicas instrumentales con intensidades ≥ VII EMS: terremoto de Lorca, España (11/05/2011); secuencias sísmicas de Christchurch, Nueva Zelanda (04/09/2010 y 22/02/2011) y series sísmicas de Emilia Romagna, Italia (20/05/2012 y 29/05/2012). Los datos cuantitativos obtenidos en este trabajo revelan la coherencia de las orientaciones de las estructuras de colapso con respecto a la localización de los epicentros, independientemente de su edad, tipo y estado de conservación. La dirección de llegada de las ondas sísmicas en terremotos de campo cercano provoca caídas con orientaciones subparalelas y consistentes con otras orientaciones de daños. No obstante en yacimientos arqueológicos es necesario evaluar otras posibles causas de origen de los daños.

Palabras clave: efectos arqueológicos de terremotos (EAEs); caídas orientadas de estructuras; terremotos de Christchurch; terremoto de Lorca; terremotos de Emilia Romagna.

1. Introduction

The study of the orientation of damaged structures during recent instrumental earthquakes allows us to calibrate and improve archaeoseismic analytical methods. These methods are based on the analysis of the recorded dominant directions of damage (Earthquake Archaeological Effects, EAEs) at archaeological sites or historic buildings (Rodríguez-Pascua *et al*., 2011) leading the analysis of the possible seismic origin of the recorded deformations.

The main problem to perform this kind of "analytical archaeoseismology" study is the calibration the analysis methods as well as the establishment of the relationship between the oriented damage and the corresponding seismic focal parameters (e.g. epicentre location, fault orientation and type). This task is difficult to define for historic earthquakes affecting archaeological sites or the historical heritage, where in most of the cases the respective location of the macroseismic epicentres are theoretical and suspect seismogenic faults are poorly defined. In this way, the study of damage orientation for recent earthquakes occurred during the instrumental period allow us to cross-check, test and calibrate the analytical methods improved for the analyses of ancient earthquake damage in the historical heritage (e.g. Giner-Robles *et al*., 2009, 2011). This paper analyzes oriented fallen structures associated with three instrumental seismic series, with epicentral intensities ≥ VII EMS: Christchurch seismic sequences (New Zealand, September 2010 and February 2011); Lorca Earthquake (Spain, May 2011); and Emilia Romagna earthquakes (Italy, May 2012).

2. Metodology

The methodology used in this paper, developed by Giner-Robles *et al*. (2009, 2011) to analyze seismic-induced strain on building fabric at archaeological sites, involves a number of stages (Fig. 1):

- Damage identification and inventory (geological effects and effects on building fabric).
- Data characterization (type of effect and measurement).

Before analyzing the different observed deformations, several aspects regarding the

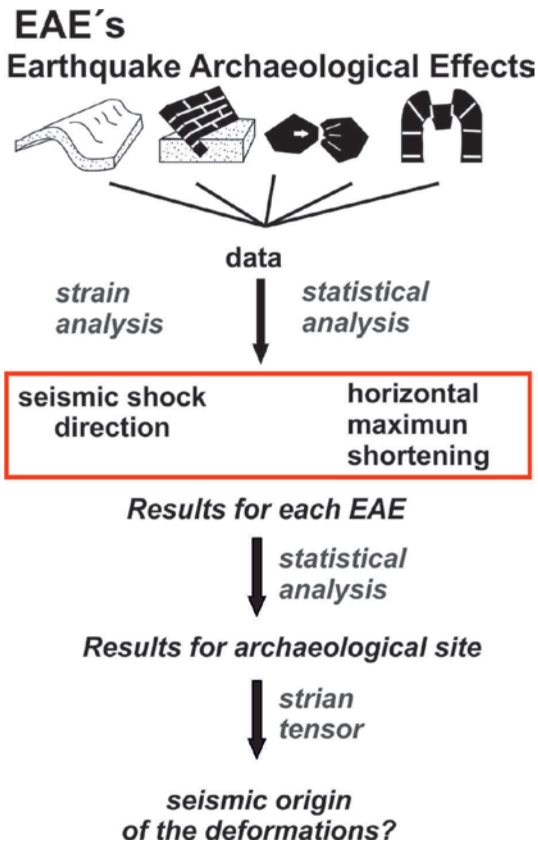

Figure 1. Method diagram proposed by Giner-Robles *et al*. (2009) for the quantitative analysis of strain deformation present in structures on an archaeological site (EAE) (Rodríguez Pascua *et al*., 2009, 2011).
Figura 1. Diagrama método propuesto por Giner-Robles et al. (2009) para el análisis cuantitativo de deformación cepa presente en las estructuras en un sitio arqueológico (EAE) (Rodríguez Pascua et al., 2009, 2011).

collection of data must be considered. These aspects focus on defining the parameters to be analyzed to provide strain tensor data and to ensure suitable characterization of the deformation kinematics.

– Strain quantification on each analyzed structure (EAE).
– Analysis of the tensors defined for each EAE (a single result for each EAE recorded at the site) so that the consistency of the data throughout the site depending on the type of EAE can be analyzed.
– Overall site analysis, so that the homogeneity of the entire data-set for a single site can be assessed and where applicable, measured against the defined strain tensor.

The recorded damage on building fabric can be of various types as described in the classification of EAEs performed by Rodriguez-Pascua *et al*.(2011): folded or buckled mortar floors and pavements, pop-up type structures, conjugate slab fractures, impacts between slabs, impact marks on blocks; tilted, folded or displaced walls, penetrative fractures on masonry blocks, conjugate fractures on stucco or brick walls, collapsed walls, folded and displaced buttresses, oriented column falls, breakage on corners of blocks, displacement in arches and lintels on doors and windows, rotation in masonry blocks and columns and displaced stone blocks. In this paper we focus on the analysis and interpretation of oriented fallen structures occurred during the aforementioned earthquakes in Spain, New Zealand and Italy.

In archaeoseismological analysis, it is very common to consider the oriented fall of columns as an evidence of near-field seismic activity (Nur and Ron, 1996; Stiros, 1996). Many authors consider that oriented fallen columns indicate the arrival direction of surface seismic waves; i.e. columns fall in the opposite direction to that of the arriving seismic waves (Fig. 2; Nur and Ron, 1996). Some authors consider that the orientation of fallen can significantly be affected by other factors, such as the type of construction (e.g. quality of materials, imperfections), anthropogenic activity (e.g. deliberate destruction) (Ambraseys, 2006; Marco, 2008), or topographic nature (e.g. slopes, escarpments) (Silva *et al*., 2009). Other authors (Hinzen, 2009; Hinzen *et al*., 2009) use cyclical movement models of these structures to indicate that small changes in the energy and even duration of the vibration can lead to columns falling in different azimuths. However finite-elements models developed by these authors only consider single and isolated columns and do not take into account that for most of the cases of archaeoseismological damage columns was active structural

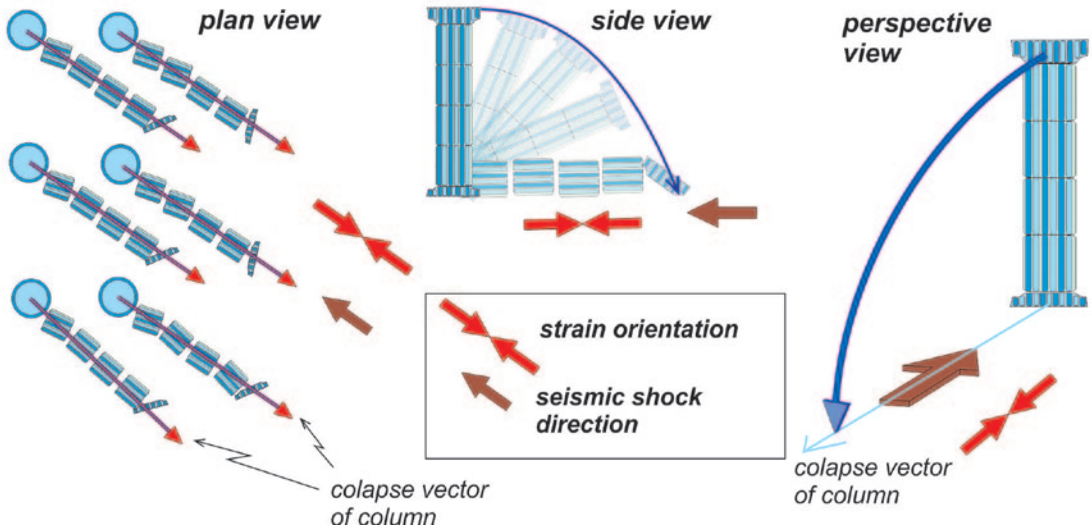

Figure 2. Analysis of structure deformation in oriented column falls. The direction of maximum strain (ey) is parallel to the orientation in which the columns fall. Damage directionality is defined by the sense in which the column falls (Giner-Robles *et al*, 2011).

Figura 2. Análisis de la deformación en estructuras de caídas orientadas de columnas. La dirección de máximo acortamiento horizontal (ey) es paralela al sentido de caída de las columnas. La direccionalidad de los daños está definida por el sentido de caída de la columna (Giner-Robles et al, 2011).

elements of ancient buildings connected with other key structural elements such as roofs, timbers and walls (e.g. Stiros, 1996; Ambraseys, 2006). Consequently seismic ground-motion affected to the whole ancient building and a pull-effect can be expected.

Therefore, in order to avoid misinterpretations in the study of this particular EAE, its analysis should be conditional upon the number of fallen columns involved and the surface area where they appear. A significant number of fallen columns has to be analyzed, preferentially belonging to different buildings or structures, and the greater the area where these structures appear, the lesser the local effects will be.

To properly quantify the occurrence of this particular EAE (Rodríguez-Pascua *et al.*, 2011), we studied systematically this type of collapsed structures in areas affected by instrumental earthquakes. These earthquakes with intensities equal to or greater than VII are the Chritschurch seismic sequences of September 2010 (7.1 Mw) and February 2011 (6.3 Mw), the Lorca Earthquake in May 2011 (5.2 Mw), and the earthquakes of Emilia Romagna in May 2012 (5.9 Mw and 5.8 Mw).

3. Analysis of oriented fall structures

3.1. Christchurch seismic sequences

The Christchurch seismic sequences (New Zealand) of September 2010 and February 2011 generated two destructive events on 04/09/2010 (7.1 Mw) and 02/22/2010 (6.3 Mw) produced remarkable damage in the city. The second earthquake was located in the outskirts of the city (SW), less than 2 km away from the city centre producing extensive damage at intensity level VIII to IX MM. After the second sequence the Central Business District (CBD) was closed and field-survey was no possible at the city centre. For this reason we choose the churchyards and cemeteries around the city for the analysis. The Cemeteries have many elements and structures able to record oriented falls, such as a large number of columnar structures, obelisks and tombstones (Fig. 3). The recorded orientations of the fallen structures were very homogeneous, with small dispersions due to the particular geometry of the affected structure (e.g. rounded or squared bases). In some cases there were two well defined orientations. They have been provisionally interpreted as the result of the two seismic shocks related to the first and second seismic sequences that struck the city.

3.2. Lorca Earthquake, 2011

The Lorca earthquake (Spain) of May 11th, 2011 (5.2 Mw), whose epicenter was located very close to the city (c. 3 km NW Lorca) caused extensive damage of intensity VII EMS (IGN, 2012; Martínez Solares *et al.*, 2012). Among the 140 recorded EAEs (IGME, 2011; Giner-Robles *et al.*, 2012), we analyzed 33 oriented falls structures (chimneys, balustrades, etc.) (Fig. 4).

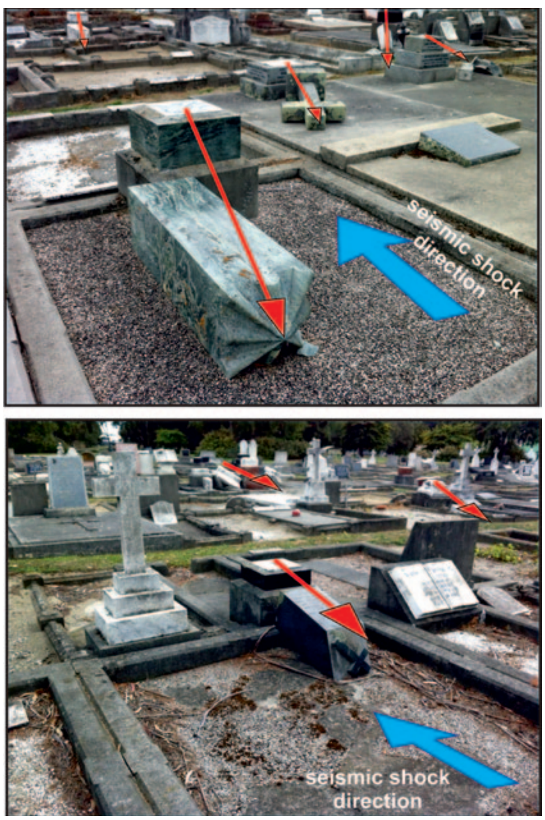

Figure 3. Oriented fallen crosses and obelisks in the Bromley Cemetery (Christchurch, New Zealand) as a result of the earthquakes that struck the town in 2011 and 2012. The azimuth of the falls is the same in the entire cemetery.
Figura 3. Caídas orientadas de cruces y obeliscos en el Cementerio de Bromley (Christchurch, Nueva Zelanda) como consecuencia de los terremotos que afectaron a la ciudad en 2011 y 2012. El azimut de las caídas es el mismo en todo el cementerio.

The various types of damages (EAEs) are distributed homogeneously throughout the city and they display orientation N130ºE with very small dispersion (Fig.4a2). This orientation is almost orthogonal to the overall orientation of the Lorca-Alhama de Murcia Fault (LAF), the seismic source of the 2011 event (IGME, 2011; Martínez Díaz *et al.,* 2012), and also coincides with the orientation of the horizontal displacement vectors, as deduced from ground acceleration data (0.37g) recorded by IGN seismic station sited at the Lorca city centre (IGN, 2012; Martínez Díaz *et al.,* 2012). The results of the analysis of the fallen structures present a parallel orientation to the direction of the horizontal displacements recorded during the earthquake (Fig.4b1). The azimuths of all structures can be grouped at N310º (NW) and at N130º (SE). This bimodal distribution on the oriented damage is conditioned by the geographical location of the EAEs in relation to the trace of the seismogenic fault (LAF) NW of the city (Giner-Robles *et al*., 2012). However, all of the oriented structures have azimuths indicating displacement to the NW, consistent with the location of the fault trace. In spite of in few cases there is some dispersion (Fig.4c and d), most of the recorded orientations are subparallel and consistent with other architectural damage recorded in the city.

3.3. Emilia Romagna Earthquakes

The seismic sequences of Emilia Romagna (2012, Italy) of May 20 (5.9 Mw) and May 29 (5.8 Mw) produced oriented damages, mostly wall collapses and oriented falls. Field survey carried out for this zone included the analysis of EAEs in about eleven localities around the epicentral area immediately after the second earthquake, comprising a radius of c. 30 km

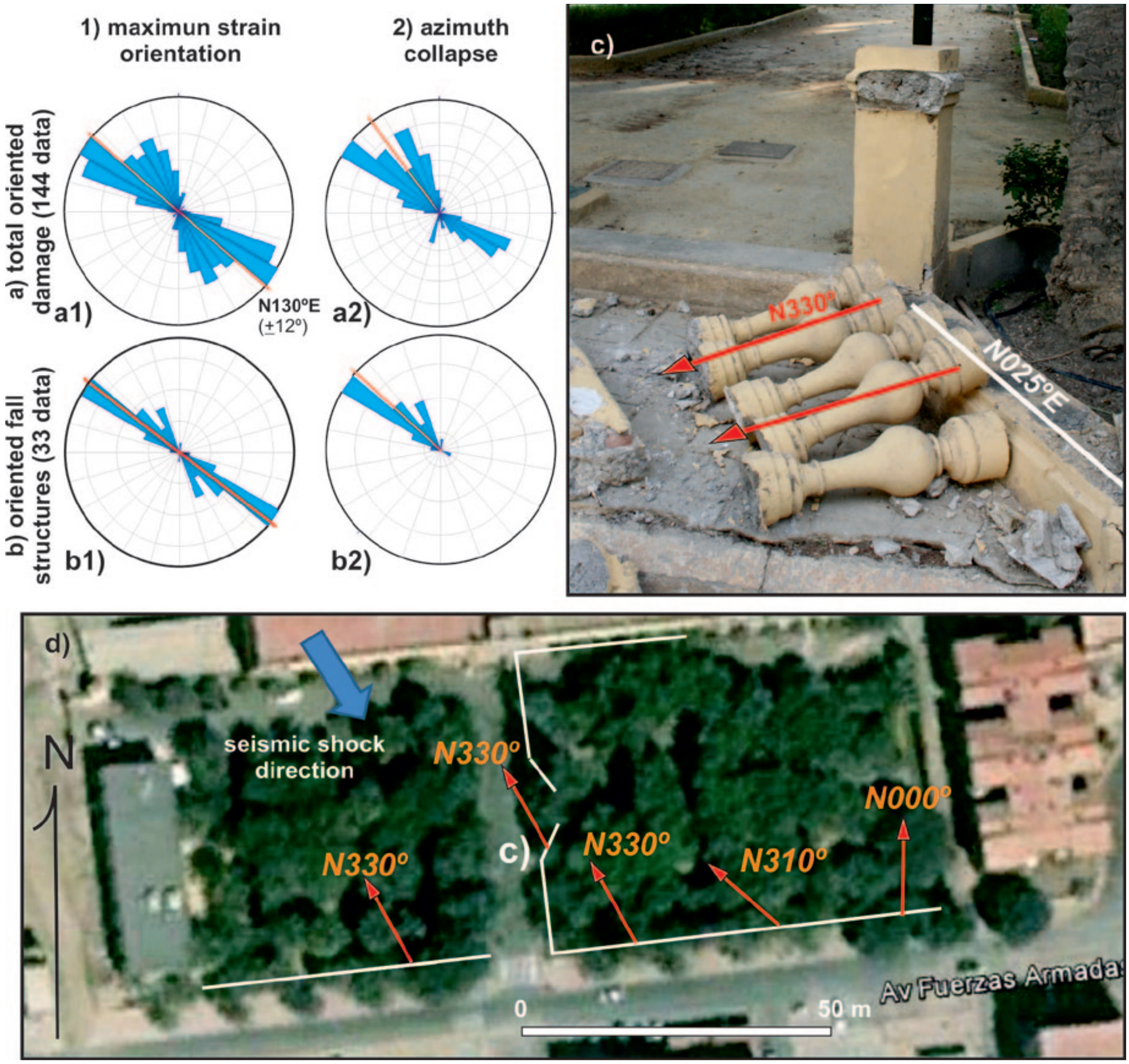

Figure 4. Rose diagrams of maximum deformation (ey) (1) and azimuth of the collapse structures (2), of all the recorded damages (a) and oriented fall structures (b). c) Detail of a fall on the balustrade in a city park in Lorca. d) Map illustrating the consistency in the measured directions of maximum deformation and in the azimuth of collapse.
Figura 4. Rosas de orientaciones de máxima deformación horizontal (ey) (1) y de azimut de caída (2), de todos los daños registrados (a) y sólo de las estructuras de caídas orientados (b). c) Detalle de una caída en la barandilla en un parque de la ciudad de Lorca. d) Mapa que ilustra la consistencia en las direcciones de deformación máxima y de azimut de caída.

(Pérez-López *et al*., 2012). The preliminary analysis of the orientation of maximum deformation (Giner-Robles *et al*., 2011) displayed two orthogonal directions (N330º and N240º; Fig. 5) that may represent the occurrence of the two main earthquakes or be related to the orientation of the suspect seismic fault. This corresponds to a buried reverse fault (N130º) under the thick sedimentary sequence of the Po Plain (Lavecchia *et al*., 2012). Consequently, N330º oriented falls will be parallel to fault orientation, and the orthogonal N240º ones parallel to the reverse fault displacement (Pérez-López *et al*., 2012).

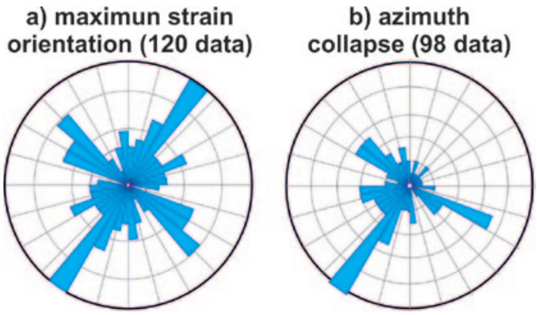

Figure 5. Rose diagrams of maximum deformation (ey) (a) (120 data) and azimuth of the collapse structures (b) (98 data), of all the recorded seismic damages measured (Emilia Romagna, Italy). The data were measured at 14 locations in the Emilia Romagna affected by the two series of earthquakes (30 km around the epicenters).
Figure 5. Rosa de orientaciones de máxima deformación horizontal (a) (120 datos) y de azimut de caída (b) (98 datos) de todos los daños sísmicos registrados (Emilia Romagna, Italia). Los datos se han medido en 14 localidades afectadas por las dos series de terremotos (30 km alrededor de los epicentros).

Data presented in this study corresponds to the epicentral area of the second event (5.8 Mw) recorded in the localities of Mirandola and San Giacomo Roncole, located 6 to 7 km NW of the earthquake epicenter, which underwent damage at VII-VIIIEMS Intensity (ISPRA, 2012). In the cemetery of Mirandola, oriented EAEs were observed in single structural elements (e.g. obelisks, tombstones), but also in complex elements such as columned atriums. In the central part of the cemetery there was a fallen obelisk oriented in a N270º azimuth (Fig. 6). A detailed analysis shows that the square base of the obelisk records a rotation and a shift towards N340º (Fig. 7a). It is also observed that the upper northwest corner of the base (Fig. 7c) show a distinctive break-out defining a seismic shock towards NW according to the methodological approach of Giner-Robles *et al.* (2012). Cracks are not observed in the SE corner (Fig. 7b) which is consistent with the displacement vector of the shifted base (N340º). In the south of the cemetery, a battery of columns fell oriented. The columns collapsed obliquely to the direction of the structure with a N340º azimuth (Fig. 8), consistent with the rest of the documented oriented damage.

Orientated obelisk towards N270º is conditioned by the presence of squared slabs between the basement of the monument and the circular base of the overlying obelisk, but is clearly controlled by the seismic shock direction. This orientation (N340º) is clearly observable in the shifted base of the obelisk (Fig. 6a) and in the fall of all the atrium columns in the southern part of the cemetery (Fig. 8).

In the locality of San Giacomo, seismic damage was recorded in a single obelisk placed in the front door of the church's town. In this case, the structure did not collapsed, but clearly shows that the characteristics of the construction might conditioned the direction of displacement of the obelisk. This obelisk has been displaced towards the only possible direction that allows the structure (Figs. 9a and 9b), but the break-outs in the block illustrate the actual orientation of the ground movement (N250º), parallel to the collapse of the gable of the church (N240º) south of the obelisk (Fig. 9c).

4. Discussion and Conclusions

The oriented collapsed structures reported at near-field seismic locations of three instrumental earthquakes indicate that these structures display very uniform fall orientations in relation to the location of their corresponding seismic sources. Moreover, the recorded azimuths seem to be independent of the intrinsic features of the analyzed structures (e.g. type, age, conservation stage and building materials). The structures analyzed in Spain, New Zealand and Italy are made with different materials (brick, concrete and masonry blocks) are of very different ages (18^{th}, 19^{th} and 20^{th} centuries) and of different types, such as tombstones, obelisks, single and batteries of columns (balustrades, atriums).

Some dispersion is observed in a few cases, but in most of them the small variations in orientation can be related to the intrinsic structure of the damaged elements. Small variations in the

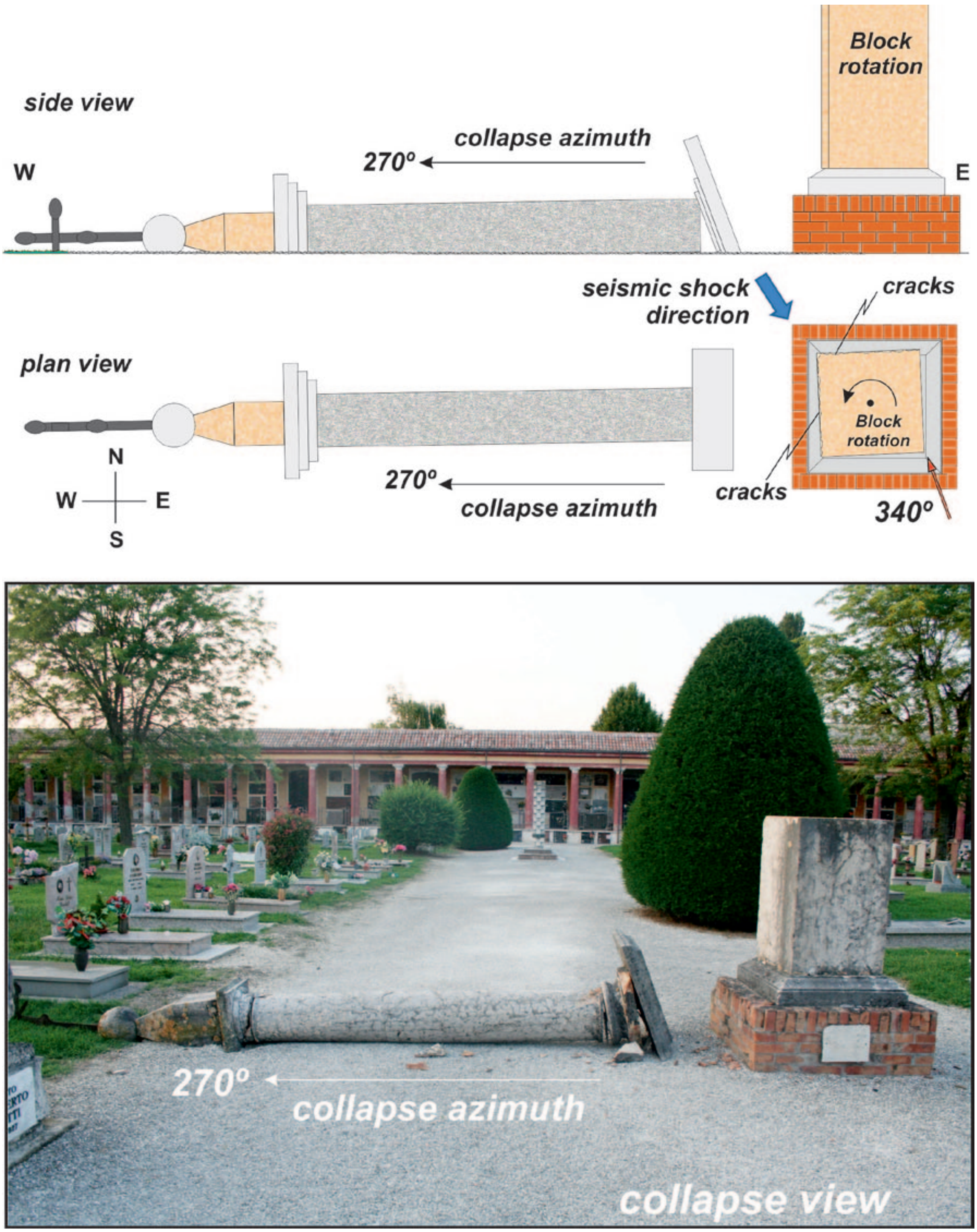

Figure 6. Structure collapsed in the cemetery of Mirandola city (Mai 29 earthquake, Emilia Romagna, Italy). Scheme (a) and photograph (b) of the collapsed structure. The obelisk collapses towards the N270º, while the base undergoes rotation and displacement (N340º).

Figura 6. Estructura colapsada en el cementerio de la ciudad de Mirandola por el terremoto de del 29 de mayo de 2012 (Emilia Romaña, Italia). Esquema (a) y fotografía (b) de la estructura colapsada. El obelisco cae hacia N270 º, mientras que la base gira y se desplaza en hacia los 340º.

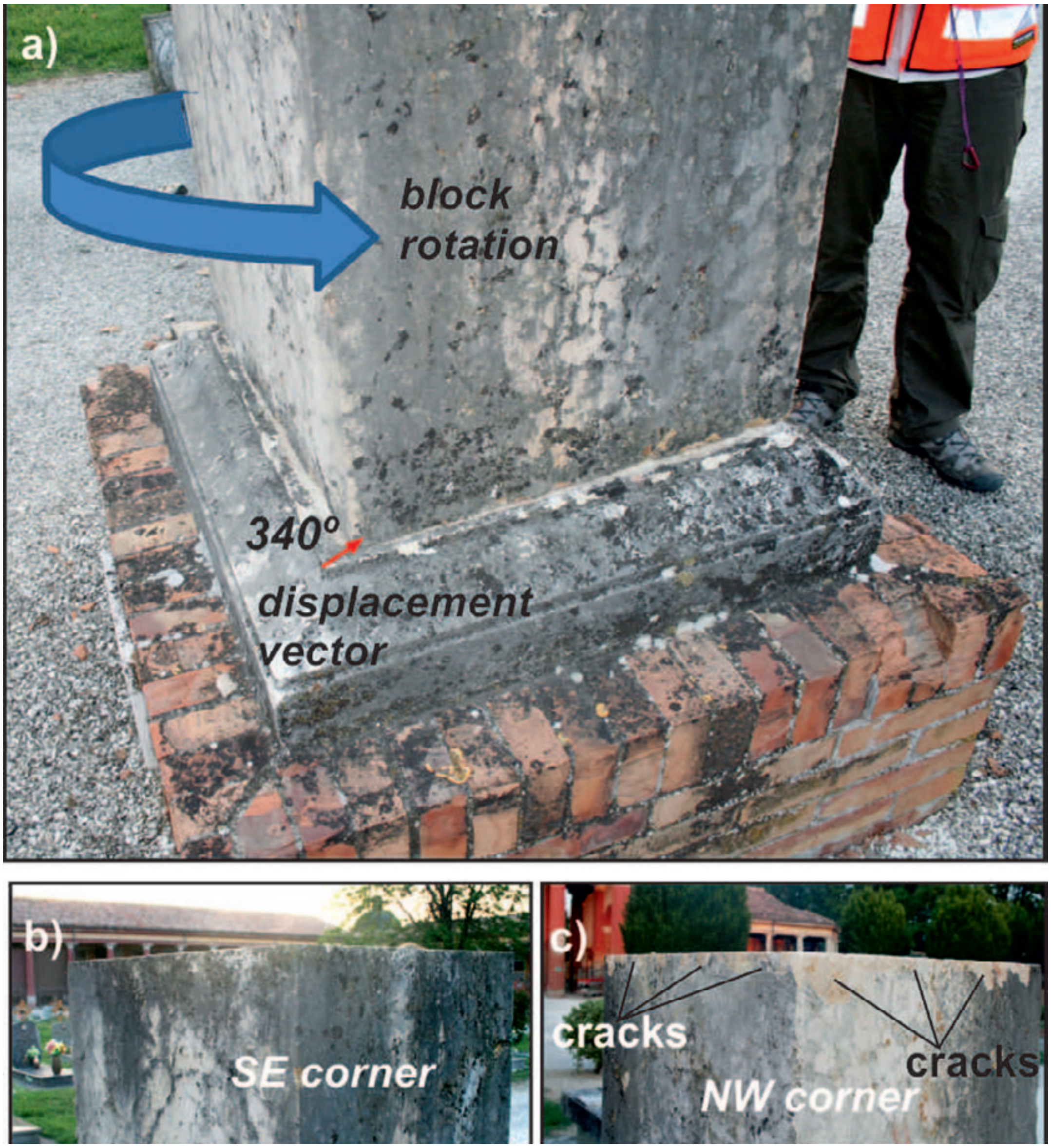

Figure 7. a) View from the SE of the base of the obelisk. Note its rotation and displacement as N340º. Views of the top corners of the obelisk base: the SE corner (b) shows no damage, while the NW corner (c) shows cracks as a result of a NW- oriented seismic shock, parallel to the displacement of the base.

Figura 7. a) Vista desde el SE de la base del obelisco. Nótese la rotación y desplazamiento hacia 340 º. Vistas de las esquinas superiores de la base obelisco: la esquina SE (b) no muestra ningún daño, mientras que la esquina NW (c) muestra grietas como resultado de golpe sísmico orientado según NO, orientación paralela al desplazamiento de la base.

shape and/or geometry of the structure (i.e. shape of the base of the structures, relationships with the other walls or structures) can produce dispersions in the orientation of the coseismic fall. However, in all cases analyzed the results display well-defined maxima in collapse orientations, otherwise consistent with those obtained for other EAE indicators. Moreover, the systematic and detailed analysis allows to establish the direction of the seismic shock triggering oriented collapses in a variety of structures, reducing the dispersion of the orientations, and consequently on the computed directions of maximum deformations.

Figure 8. Series of columns collapsed in the cemetery of Mirandola. The azimuth coincides with the displacement vector of the base of the obelisk (see fig.5).

Figura 8. Grupo de columnas colapsadas en el cementerio de Mirandola. El acimut de caída coincide con el vector de desplazamiento de la base del obelisco (ver figura 5).

The field-survey and analysis of structures collapsed during instrumental earthquakes will help to the analysis and interpretation of similar oriented fall structures in archaeological sites. The modeling of the response of these structures to local seismic sacking is necessary, but when a numerous set of oriented fallen elements occur in agreement to fault-source parameters (e.g. epicentral location, fault motion), their seismic origin can be assessed. In all the cases the recorded oriented damage presented in this study was documented at small epicentral distances of 2 (Lorca and Christchurch) to 6 km (Mirandola), but field surveys in the Emilia Romagna case extended to epicentral distances over c. 20 km recording similar oriented EAEs (Pérez-López *et al.*, 2012). In this sense is interesting to highlight that the study developed in this paper gather different cases: One earthquake – one locality (Lorca, 2011); Two earthquakes – one locality (Christchurch, 2012); Two earthquakes – several localities (Emilia Romagna, 2012). The first two cases can illustrate the common cases representative for archaeoseismological analyses (e.g. Silva *et al.*, 2009), where suspect oriented damage is difficult to relate to any known seismogenic source. On the other hand, the Emilia Romagna case can be representative of some known historical earthquakes where structural damage data are available for several localities around the epicentral area (e.g. Stiros, 1996 and references therein).

The EAEs analysis presented in this work points out that in epicentral areas (< 10 km) of moderate-strong earthquakes (5.0 – 6.5 Mw), oriented falls occur with regular azimuth directions consistent with the available fault-source parameters. The recorded limited dispersion on fall orientations can

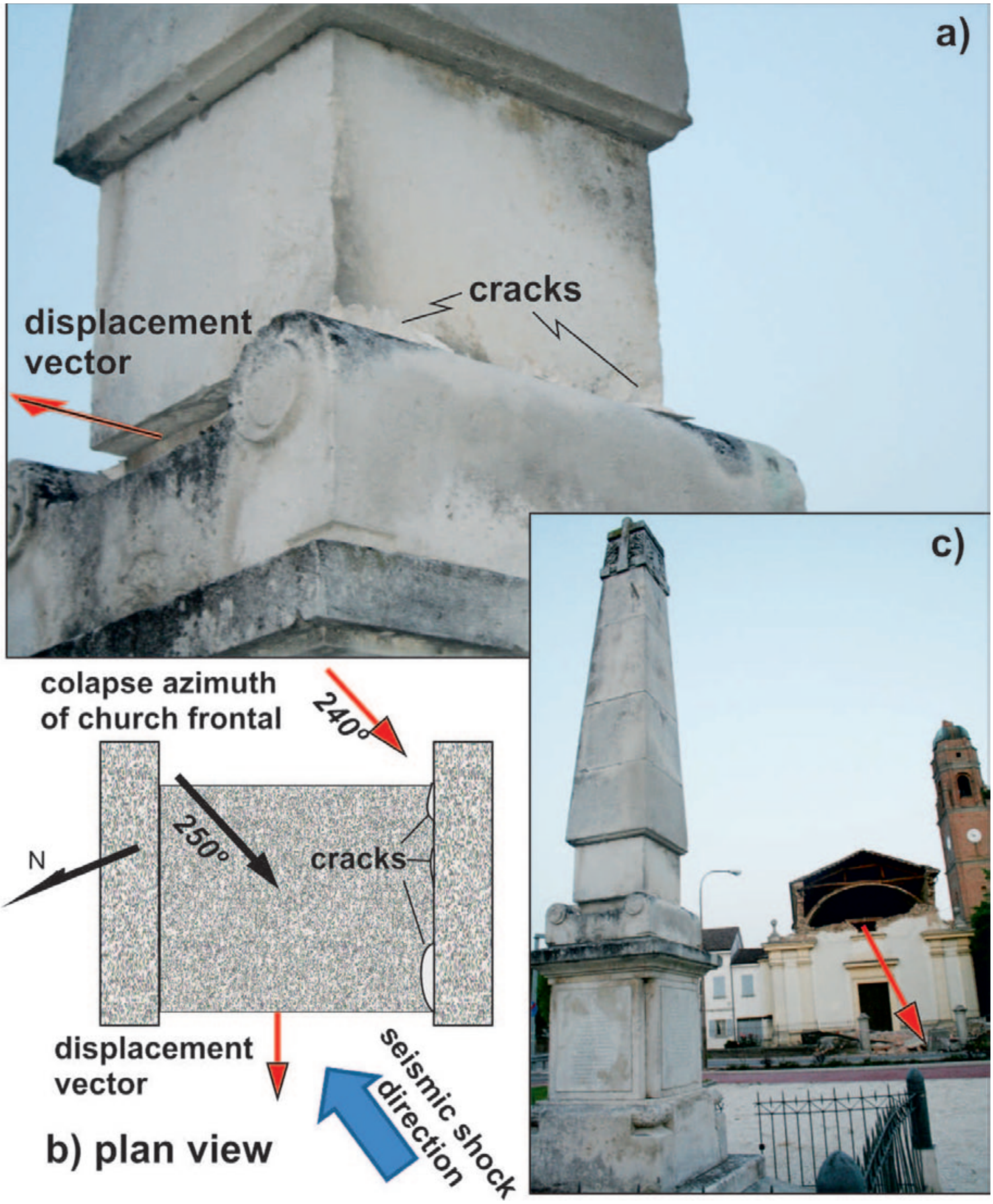

Figure 9. Obelisk in the village of San Giacomo Roncole. Displacement occurred in the only possible direction (a, b), but cracks in the block indicate the direction of the maximum strain, subparallel to the collapse of the facade of the church in the background (c) (N240º).

Figura 9. Obelisco situado en el pueblo de San Giacomo Roncole (Emilia Romagna, Italia). El desplazamiento se produjo en la única dirección posible (a, b), pero las grietas en el bloque indican que la dirección de la deformación máxima presenta una orientación subparalela al acimut de colapso de la fachada de la iglesia que si sitúa al fondo de la fotografía (c) (N240 º).

be related to specific characteristics of the damaged structures and complementary analyses are necessary. More comprehensive analyses covering the different EAEs recorded in earthquake macroseismic areas are required in order to provide consistent relationships between EAEs orientations and earthquake focal parameters. The study cases indicate that the archaeoseismological analysis of ancient earthquakes based in this methodology can help to put constrains in the identification of suspect seismic sources, and consequently to improve future seismic hazard analyses.

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