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SENSITIVITY ANALYSIS OF THE SEISMIC RESPONSE OF BRITTLE STRUCTURAL ELEMENTS UNDER NEAR-FIELD SEISMIC INPUT EFFECTS

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Abstract. *This research provides a sensitivity analysis, taking into account possible variations on the structural response of a specific type of brittle masonry vaults under near-field effects. Ground motions from the near- field contain distinct pulses in acceleration, velocity, and displacement histories, which can generate higher base shears and drifts, than signals from the far-field. Besides, under those inputs, the ductility demand could be increased. In a first step, the worst seismic scenario in the highest seismic area of the Iberian Peninsula under the premises of near-field loading is defined. The obtained seismic inputs are directly related to the structural properties of singular masonry vaults, which are representative of precious local constructions. In a second step, the sensitivity analysis, focused on the material properties, is carried out by means of non- linear transient analysis. A constitutive law for brittle materials able to capture collapse mechanism under dynamic loading via FEM is implemented. From those analyses, the influence of different control parameters on the structural response is identified, and deviations on the seismic response are analysed in terms of collapse mechanisms.*

1 INTRODUCTION

Brittle structures located in seismically active areas are especially prone to suffer structural damages, as they exhibit high vulnerability under horizontal actions, being critical for their preservation to assess seismic safety in order to evaluate their dynamic response and, if necessary, to improve their structural strength.

Strong ground motions from the near-field are the most severe earthquake loading that brittle structures undergo. The dynamic response of a structure is strongly affected by characteristics of the earthquake, such as intensity, duration and frequency content. The features of ground motion in the proximity of an active fault can be significantly different from those in the far-field.

With regards to the sensitivity and parametric analyses, it is worth noting that the sensitivity assessment of the seismic response parameters to the uncertain modelling variables is a recognized and validated method (e.g. [1, 2, 3, 4]). Uncertainties in the characteristics of the structural component (both mechanical and geometrical) are crucial and have a great impact on the response corresponding to the limit states of damage limitation and significant damage.

From the aforementioned, this research provides a structural safety analysis, taking into account possible variations on the structural response of a specific type of brittle masonry vaults (the medieval structures of the Axarquía, Spain) under near-field effects.

The present paper is arranged in two sections: the first section focuses on the analysis of the worst seismic scenario in the highest seismic area of the Iberian Peninsula under the premises of near-field loading. From that analysis, seismic inputs which are directly related to the structural properties of singular masonry vaults, are obtained. In the second section, sensitivity analyses are carried out by means of non-linear transient analysis. As far as the brittle behaviour is concerned, a constitutive law for brittle materials able to capture collapse mechanism under dynamic loading via FEM is implemented. From those analyses, the influence of different control parameters on the structural response is identified, and deviations on the seismic response are analysed in terms of collapse mechanisms.

2 THE NEAR FIELD SEISMIC INPUT

From a seismological perspective, the near field can be defined as all positions within a small fraction of a wavelength from the source [5]. From a structural perspective, the near-field is related with the potential for ground shaking of sufficient intensity to cause structural damage. In general, any distance less than 50 or 65 kilometres should be considered near for exposure to a major earthquake [6]. Near-fault ground motions are narrow-banded in nature and are characterized by a predominant period, and structures excited by them are severely affected [7]. Under those conditions, the motion may strongly depend on the complex coupling of the seismic source, rupture process, source-site travel path and local site conditions [8, 9]. Strong near-fault ground motion is usually characterized by a long period impulsive motion in the horizontal direction, with large amplitude both in displacement and incremental velocity [10]. Moreover, near-fault strong motions exhibit large incremental velocities which can give rise to large inelastic deformations of the structure regardless of the peak ground acceleration [10]. In addition, features of near-field ground motions such as directivity, can significantly enhance the destructive potential in small to moderate magnitude events [11]. The near-field directivity effects can result in high spectral ordinates at longer periods and their amplifying effects are not a monotonically increasing function with period but rather a narrow band effect at a period that increases with earthquake magnitude [12]. Furthermore, it has been demonstrated that near-field directivity effects not only need to be considered for earthquakes of moment magnitude 6.5 and greater [12]. Thus, near-field effects should be considered for all earthquakes at short distances from the sites of important or brittle structures, regardless of magnitude at least down to a lower limit that may be as small as 5 or even lower. Directivity effects in small to moderate magnitude events may be of more importance than in very large magnitude events for which the period of the near-field pulse will generally be beyond the range of most structures [12].

A main concern is that in spite of the availability of large digital input databases in many seismically active regions of the world, relatively few good quality strong motion records are available in near-field conditions [8]. Due to the lack of adequate data from close earthquakes, equations to estimate the motion are usually derived from intermediate and far-fields records. Ambraseys and Douglas presented strong-motion attenuation relationships for peak ground acceleration, spectral acceleration, energy density, maximum absolute input energy for near-field inputs [13]. That research highlights some of the singularities of those inputs (e.g. the ratio of the maximum peak ground acceleration to maximum horizontal, the significant distance dependence, …). Moreover, as the effects of near-fault motions can be variable depending on the ratio between the pulse period of the motion and the fundamental vibration period of the structure, peak ground acceleration can be inadequate to represent the structural damage potential of long-duration impulsive motions recorded near active faults [9]. The implication of possible near-field effects and destructive ground motions is related on how the hazard is evaluated. Therefore, inputs from hazard analyses are required.

As far as the Code framework is concerned, the design provisions provided by the Codes, take into account the effects of far-fault ground motions, but can be inadequate for near-fault motions [9]. Although the existing seismic codes consider near-fault shaking effects in the development of elastic response spectra, they do not currently consider the increased inelastic demands that may occur during near-fault ground motion [11]. At Present, Eurocode 8 [14] does not give specific guidelines to take into account the effects of near-fault ground motions in the design of brittle structures. According to that Code, only for base isolated buildings of importance class IV, located at less than 15 km from a known seismic source with a surface-wave magnitude M_s >6.5, the site-specific response spectra should be considered (under time-history analyses).

2.1 Hazard analysis and seismic input

The analysed structures are located at Salares and Árchez, Southern Spain, in the Betic Cordillera, the zone with the highest seismic hazard in the Iberian Peninsula. On a time scale, the seismicity is characterized by a high microseismic activity rate for magnitudes lesser than 4.5, and less frequent earthquakes of magnitudes between 4.5 and 6.5 which generated important damages in the past (e.g. the 1884 Earthquake) in the Granada basin and Málaga [15]. A seismic catalogue is constructed to define the historical seismicity of the area, considering a radius of 300 km, Table 1.

Salares	
latitude	longitude
36,85	-4,0166667

Date	Latitude	Longitude	Intensity	Location	distance (km)
01/01/1048	38,0833	-0,9167	VIII	Orihuela.A	306,31
01/01/1169	38	-4	VIII-IX	Andujar.J	*128,01*
01/01/1406	37,25	-1,8667	VII-VIII	Vera.AL	*196,1*
24/04/1431	37,1333	-3,6333	VIII-IX	S. Granada	*46,43*
10/10/1482	38,0833	-0,9167	VIII	Orihuela.A	*306,31*
01/11/1487	36,8333	-2,4667	VIII	Almería	*138,07*
26/01/1494	36,5833	-4,3333	VIII	S. Málaga	*40,98*
05/04/1504	37,3833	-5,4667	VIII-IX	Carmona.SE	*141,72*
09/11/1518	37,2333	-1,8667	VIII-IX	Vera.AL	*199,83*
22/09/1522	36,9667	-2,6667	VIII-IX	W.Alhama de Almería.AL	*120,84*
30/09/1531	37,5333	-2,7333	VIII-IX	Baza.GR	*136,86*
21/10/1578	35,2667	-2,9333	VIII	Melilla	*201,38*
31/12/1658	36,8333	-2,4667	VIII	Almería	*138,07*
15/01/1673	38,0833	-0,9167	VIII	Orihuela.A	*306,31*
28/08/1674	37,6833	-1,7	VIII	Lorca.MU	*225,18*
09/10/1680	36,8	-4,6	VIII-IX	NW. de Málaga	*52,27*
13/01/1804	36,0833	-3,5833	VII-VIII	Mar de Alborán	*93,74*
25/08/1804	36,7667	-2,8333	VIII-IX	Dalías.AL	*105,86*
27/10/1806	37,2333	-3,7333	VIII	Pinos Puente.GR	*49,54*
25/12/1884	37	-3,9833	IX-X	Arenas del Rey.GR	***16,96***
16/06/1910	36,6667	-3,3667	VIII	ADRA.AL	61,44
21/03/1911	38,0167	-1,2167	VIII	LAS TORRES DE COTILLAS.MU	279,45
03/04/1911	38,1	-1,2	VIII	LORQUI.MU	285,04
31/05/1911	37,2	-3,7	VIII	SANTA FE.GR	48,06
09/10/19	38,0833	-0,8333	VIII	JACARILLA.A	312,91
05/07/1930	37,6167	-4,6333	VIII	MONTILLA.CO	101,33
08/09/30	34,3	-5,4	VIII	AIN DEFALI.MAC	310,21
03/05/32	37,4167	-2,45	VIII	LUCAR.AL	152,65
23/06/1948	38,1417	-1,7583	VIII	CEHEGIN.MU	245,83
03/10/51	38,1833	-3,8167	VIII	LINARES.J	149,45
19/05/1951	37,5833	-3,9333	VIII	ALCAUDETE.J	81,95
01/08/54	36,9333	-3,8833	VIII	ARENAS DEL REY.GR	15,06
19/04/1956	37,1917	-3,6833	VIII	NW PURCHIL.GR	48,21
09/06/1964	37,7367	-2,5667	VIII	SW GALERA.GR	161,93

Table 1: Seismic catalogue.

From a literature review, the Ground Motion Prediction Equation proposed by Ambraseys and Douglas for the near-field [13] is selected as the most adequate for the area. The period range of interest includes all frequencies that are expected to significantly contribute to the non-linear response. Regarding attenuation of peak ground acceleration, PGA, a value of 0.21g is obtained.

A probabilistic seismic hazard analysis is performed. The applied theory is that of provided by Cornell [16] on the basis of the total probability theorem. The risk is calculated assuming that earthquakes occur as Poisson arrivals (Fig. 1). As the ground-motion intensity measure adopted is the acceleration, it is assumed that it is lognormally distributed. For a return period of 475 years, the obtained peak ground accelerations is 0.27g. According to EC8, this return period ascribes to a Limit State, LS, of Significant Damage, SD, corresponding to a probability of exceedance of 10% in 50 years. On the basis of these results, the relation between the structural performance criteria and the probability of exceedance related to significant LS may be provided.

As far as the procedure for input selection is concerned, an earthquake scenario-based selection is applied. The seismic hazard is disaggregated by: causative Moment Magnitude, M_w, Joyner-Boore distance, r_{jb}, and site class, at the determined probability level. Records that fall in bins around central values of seismic those parameters are selected. Those parameters are strongly related to the structural response, and are correlated to important characteristics such us frequency content, spectral amplitude, shape and duration. It is worth noting that brittle masonry structures are particularly sensitive to the frequency content of the ground motion, so parameters which measure motions at similar periods to that of the structure are better correlated with damage. The adopted intervals are: [6, 6.6] for the M_w, [0 km, 30 km] for the r_{jb} and [360 m/s, 760 m/s] for the v_{s30}, following the magnitude bin width proposed by Bommer and co- workers [17]. Records are selected from a subset of 175 strong-motions of the Pacific Earthquake Engineering Research Center (PEER database). The selected real records are treated following a linear amplitude scaling. The geometric mean spectrum of the as-recorded components x and y is used (GM_{xy}). Pre- selected records are scaled in terms of spectral acceleration for the fundamental period, S_a (T_1,5%). After scaling of the records according to spectral matching, a screening aimed at obtaining seismic input with spectral shapes similar to the target spectrum is undertaken. A root-mean-square difference equation, D_{rms}, [18] between the spectrum of each real record and the reference spectrum is used. After performing a Coefficient of Variation comparison, COV, three records which exhibit the best goodness-of-fit are selected for the EC8 compatibility (Fig. 2).

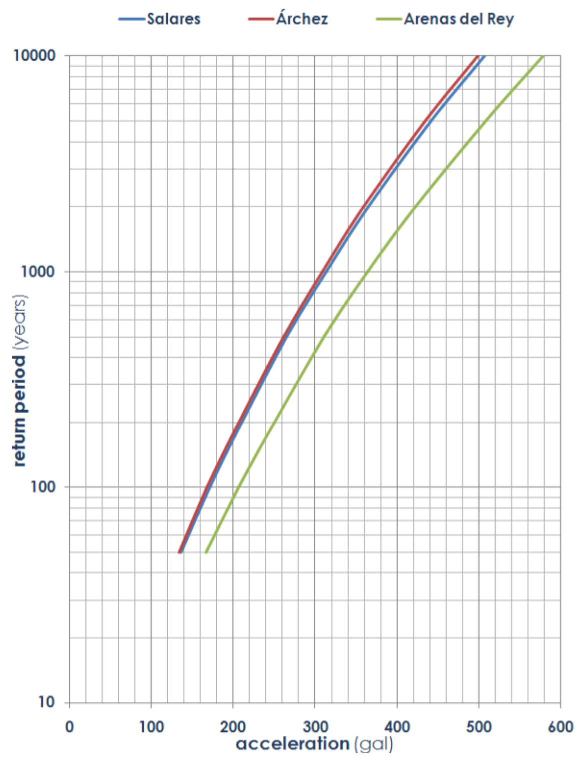


Figure 1: Probabilistic Seismic Hazard analysis.

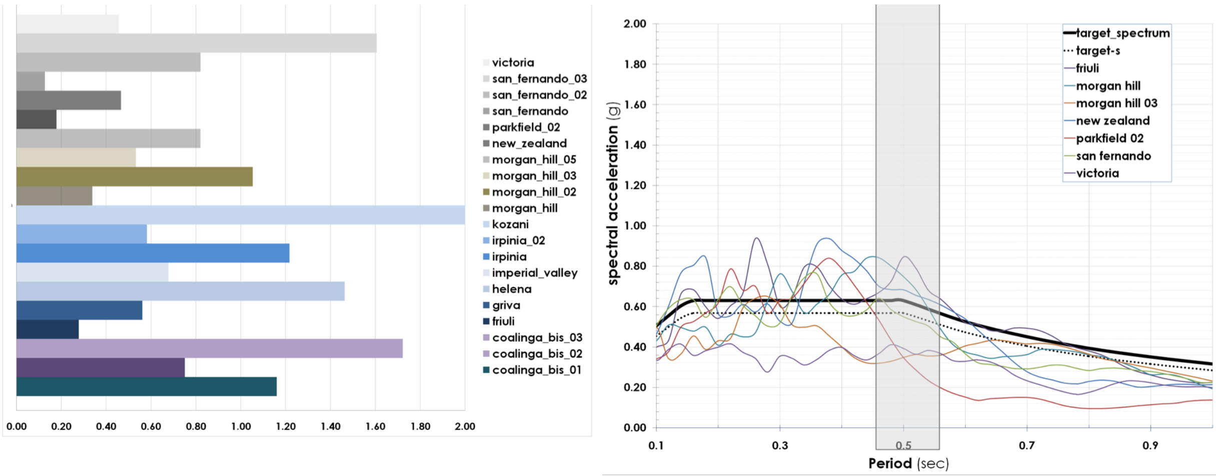


Figure 2: Record selection for the EC8 compatibility.

3 SENSITIVITY ANALYSIS OF THE SEISMIC RESPONSE

Transient analyses are performed on detailed three-dimensional finite element models, taking into account the material non-linear behaviour and the geometrical and structural properties. The ANSYS finite element software [19] is used to construct the model, and three-dimensional eight node solid elements, SOLID 65, are used for masonry material. A smeared model with homogenized properties is selected. The analysed vaults are structural elements of a medieval tower located in Salares, in the Axarquía (Fig. 3). The whole structure is built of clay bricks bonded with lime mortar. The Salares vaults are dramatically damaged (Fig. 4). Stiffness degradation as well as cracking and crushing evolution are taken into account. The Drucker- Prager, DP, perfectly plastic criterion [20] and the Willam-Warncke, WW, failure surface [21] are the selected theories. The stress-strain matrix has been adjusted by introducing a plane of weakness in a direction normal to the crack face. The expression that governs the failure of the material is:

$$\alpha\sigma + \sqrt{\frac{1}{3}\sigma^2 + \tau^2} - k = 0 \tag{1}$$

where:

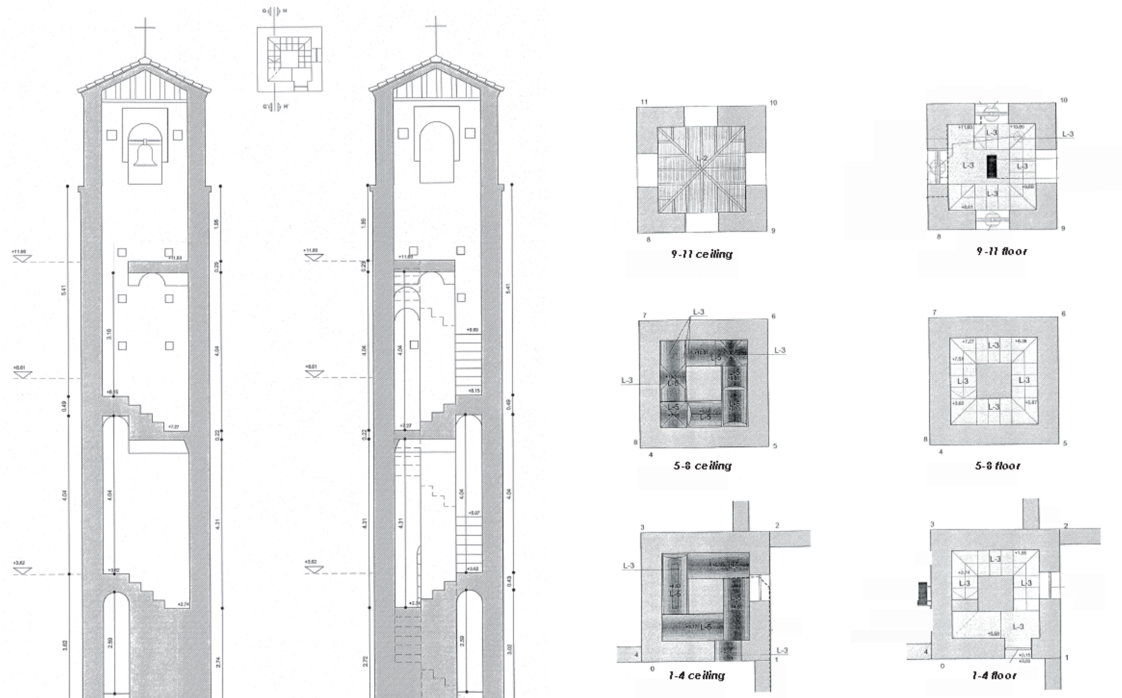
$$\alpha = \text{material constant} = \frac{2sin\phi}{(3 - sin\phi)\sqrt{3}}$$

σ = normal stress

τ = shear stress

$$k = \text{material constant} = \frac{6ccos\phi}{(3 - sin\phi)\sqrt{3}}$$

c = cohesion



L1	outside damages: variegated crack pattern, no bonded masonry
L2	roof damages: moisture, loss of tiles, deteriorated wooden structure
L3	wall and floor damages: loss of material, detachment of the outher wythe
L4	wall damages: local reconstruction with different materials, stones or poor quality bricks-
L5	wall and ceiling damages: moisture, diffused and thin cracks, loss of material

Figure 3: Geometrical and vault damage descriptions.

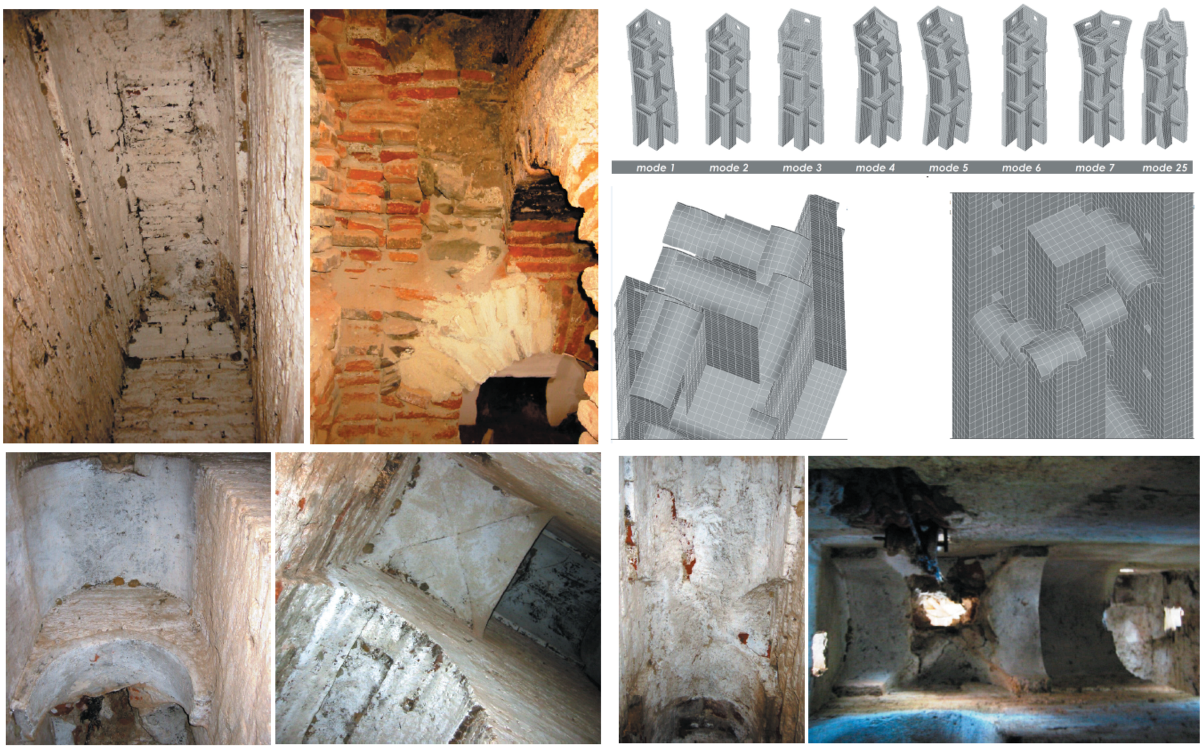


Figure 3: Vaults and FE model.

The time-dependent structural response is obtained from 3 nonlinear time-history analyses, following the component combinations proposed by EC8. The reference seismic scenario is that of previously obtained. A Rayleigh model for damping is applied. The effect of vertical loading in the near-field can be important for damaged masonry structures. Thus, in order to assess the inelastic dynamic response of these structures, the structural responses for bi and tri-directional inputs are compared.

A deterministic sensitivity analysis is used to measure the sensitivity of the seismic response to three performance levels: Near Collapse, NC, Significant Damage, SD, and Damage Limitation, DL. The return period associated to each LS, as well as the corresponding acceleration are those obtained from the probabilistic approach. In a first step, the seismic response parameters are computed for the base-case model on the basis of the best-estimate value. After this, a variation of the random variable to its 16^{th} or 84^{th} fractile is performed. The masonry compressive strength is determined by means of the equation provided by Eurocode 6, $f_{ck}=Kf_{cu}^{0.7}f_{cm}^{0.3}$, where $f_{c,k}$ is the masonry characteristic compressive strength and K, equal to 0.45 in this research, is a parameter that depends on the type of unit and on the type of masonry. The following input variables are considered: Young modulus, E, (median value 3E+09 Pa); masonry compressive strength, f_c (median value 3E+06 Pa); masonry tensile strength, f_t (median value 1E+05 Pa); the value of the friction angle (reference 54º) matches the uniaxial strengths in tension and compression at each step. Due to the low confined nature of the masonry, a reference value of 10º is adopted for the dilatancy. The value of the cohesion matches $1.5f_t$ at each step.

An extremely high cracking pattern is observed in the vaults. The analysis and comparison of the results from the bi and tri-dimensional inputs shows that the most significant gradient appears at the shear S_{xz}, with 85% growth in some time steps. The uncertainty in the mechanical parameters of the masonry, especially those of the mortar, has the greatest impact on the Limit State compliance. A comparison between the different steps reveals that stress field is influenced by sensible redistributions and high gradient values when the uniaxial strengths are varied. Shear stresses undergo dramatic decrease when the mortar compressive strength, f_{cm}, is increased (a maximum 60 % increase is observed) (Fig.5) and for the maximum f_{cm} a decrease of 55% is observed for the main period. From the dynamic response it may be concluded that the vaults do not act as rigid diaphragms and relative rotations are observed.

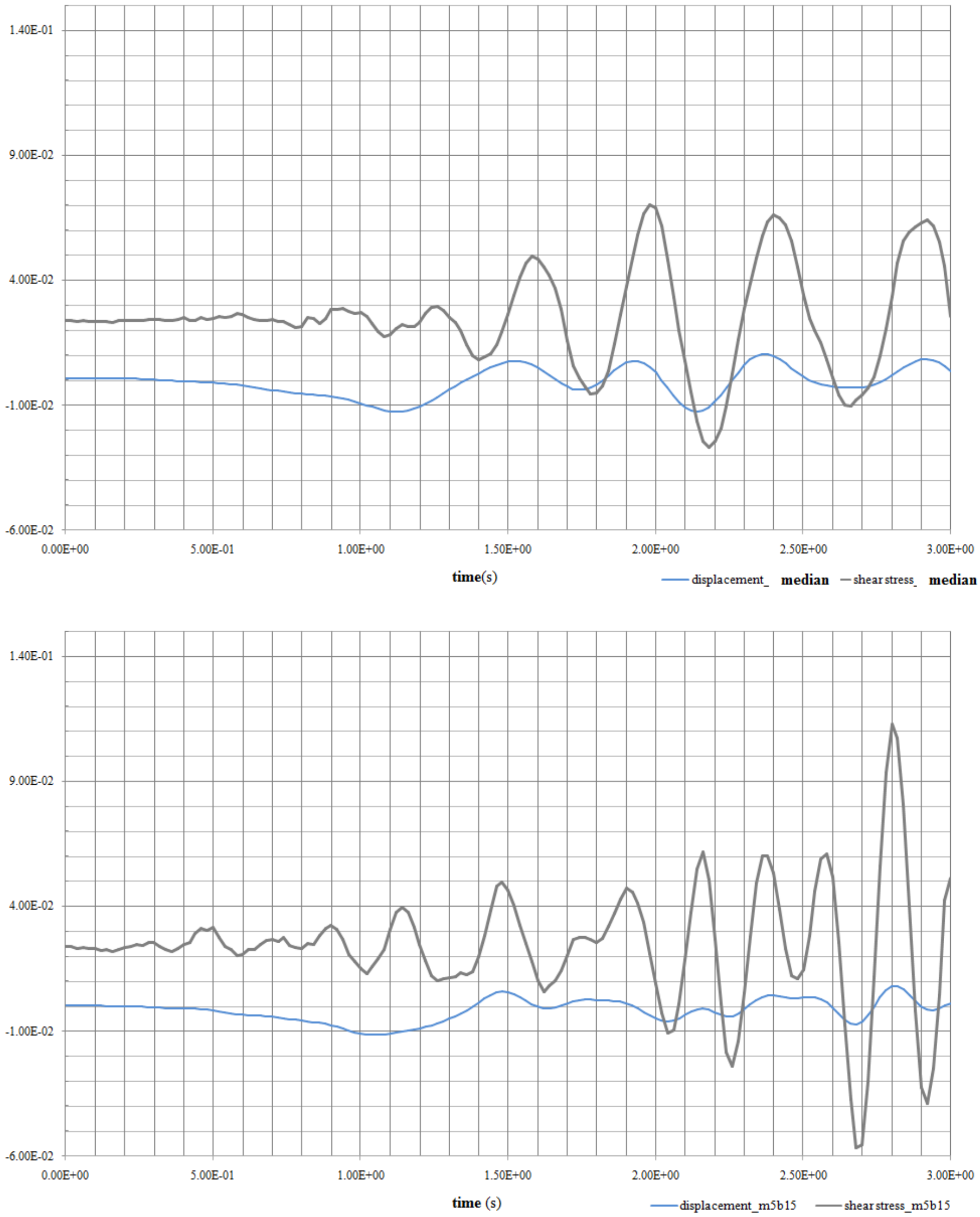


Figure 5: Transient analyses results.

4 CONCLUSIONS

- Ground motions from the near- field contain distinct pulses in acceleration, velocity, and displacement histories, which can generate higher base shear and drift than signals from the far-field.
- The worst seismic scenario in the highest seismic area of the Iberian Peninsula under the premises of near-field loading has been defined, focused on specific masonry vaults.
- The return periods ascribed to each LS are obtained from the probabilistic approach.

- A constitutive law for brittle materials able to capture collapse mechanism under dynamic loading via FEM is implemented.
- The uncertainty in the properties of the mortar has the greatest impact on the seismic response parameters.
- The analysis and comparison of the results from the bi and tri-dimensional inputs shows that the shear exhibits a significant gradient.
- Results for the expected PGA are higher than those of provided by the Codes, as near-field effects must be taken into account.

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