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# SEISMIC ASSESSMENT OF TYPOLOGICAL MASONRY BUILDINGS USING SIMULATED GROUND MOTION RECORDS: A CASE STUDY FOR AZORES, PORTUGAL

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**Abstract**

*Earthquakes are the major causes of damage and loss to the built environment, including cultural heritages, monumental buildings, and historical centres. Many regions with predominant active tectonic plates and high seismicity lack recorded ground motion datasets regarding large-magnitude events or near-field records. Among them, the Azores islands in Portugal are the regions with high seismicity. The traditional buildings from the Azores are mainly constituted of rubble stone masonry, which represents one of the weakest materials once subjected to seismic loads. The seismic performance of buildings has recently increased, given the public awareness related to damage prediction and risk mitigation during earthquakes. This study uses the stochastic finite-fault ground motion simulation approach to simulate region-specific scenario earthquakes in the Azores Plateau at bedrock. Simulations are accomplished by considering the stochastic behaviour of input-model parameters in terms of source and path attenuation effects. As a result, the dataset includes a wide range of moment magnitude and source-to-site distance due to the rupture of active faults in the Azores Plateau. Structural models are simulated using an equivalent frame model. Subsequently, analytical fragility curves are derived for these structures using the generated ground motion datasets. Results reveal that the studied structures are vulnerable to seismic actions.*

**Keywords:** Azores region, Stochastic Finite-Fault Ground Motion Simulation, Bedrock, Nonlinear analyses, Masonry structures, Seismic assessment.

## 1 INTRODUCTION

In earthquake-prone zones, earthquakes are the primary cause of fatalities and economic losses. Faial Island in the Azores Plateau experienced an earthquake of Mw=6.2 in 1998 [1]. This earthquake significantly damaged traditional masonry buildings characterised by load-bearing walls made of stone masonry and flexible timber floors. These structures are highly vulnerable to seismic damage and are prevalent on Faial Island [2]. As a result, this earthquake piqued the interest of researchers in investigating the seismic vulnerability of buildings in the area, as well as estimating potential damage and human losses that may occur in future seismic events [3]. The limited availability of recorded accelerograms for large-magnitude events in regions like the Azores Plateau presents a significant challenge for assessing the seismic performance of structures. This scarcity, particularly for severe events at short distances, has encouraged the application of synthetic records.

Several studies have investigated the seismic vulnerability of traditional masonry buildings in the Azores region. Guerreiro et al. [4] studied 30 masonry churches to identify the damage modes and possible collapse mechanisms based on in-situ observations. The observed damage was correlated with the structural typology, seismic action level, masonry quality, and previous retrofit or structural interventions. Similarly, Neves et al. [5] carried out a three-stage study that included a thorough description of the building stock, damage grade classification based on observed damage mechanisms, and seismic vulnerability assessment. The considered buildings ranged from old traditional rubble stone masonry to reinforced concrete frame structures. Their findings showed a high probability of collapse, around 30%, for intensities ranging from moderate to high (I=VII and I=VIII) according to the EMS 98 scale [6]. Ferreira et al. [7] investigated the seismic vulnerability of the historic centre of Horta in the Azores by analysing 192 buildings with a simplified vulnerability assessment method. They estimated the number of buildings likely to collapse or become unusable under various seismic intensities, linking their findings to the structures' low resistance and high vulnerability. In another study, Maio et al. [8] performed the Capacity Spectrum Method (CSM) and N2 Method on two stone masonry buildings in Faial Island to evaluate the seismic vulnerability. They utilised a set of ground motion records representative of the 1998 Faial earthquake. The results of their study indicated that retrofitting could greatly enhance the seismic resilience of at-risk structures. Zonno et al. [9] addressed the lack of recorded accelerograms by employing the stochastic finite-fault method [10] to generate representative synthetic time series of the islands affected by the 1998 Faial Earthquake. The records were used to estimate structural damage by comparing the mean damage index [11] (in Italian) and a macro-seismic method [12].

Ground motion simulations can provide alternative full time series of motions for potential scenario events in regions lacking recorded motions. Ground motion simulation techniques consist of various methodologies such as deterministic, stochastic, and hybrid models, each having specific limitations due to the modelling challenges [13]. In engineering applications, stochastic methods are more common due to their relative simplicity, as they don't require full wave propagation that relies on precise source and velocity models [10,14,15]. However, they require accurate input-model parameters to produce a ground-shaking pattern that matches the specific characteristics of real regional records. Once these methods are calibrated with input-model parameters specific to a region of interest, they can serve as powerful tools for assessing the potential impact of future earthquake hazards and disasters [16].

Within the field of earthquake engineering, ground motion simulation techniques are widely utilised to assess the impact of earthquakes on various structures such as buildings and bridges [17,18]. A rigorous analysis and validation process must be conducted to ensure the reliability of ground motion simulations in engineering applications. Previous studies in the literature have evaluated stochastic ground motion simulations for estimating seismic demand in reinforced concrete and steel structures, including works by Karimzadeh et al. [19,20] and Cao et al. [21]. A recent study by Hoveidae et al. [22] utilised stochastically simulated ground motion records to evaluate seismic damage to a historic masonry building, namely Arge-Tabriz, in Iran. Ozsarac et al. [23] employed a stochastic finite-fault method to investigate the potential of simulated records in the probabilistic seismic assessment of reinforced concrete bridges. As proposed by Motazedian and Atkinson [10], Finite-fault stochastic simulations have been tested and verified for various regions of the world from both seismological and engineering perspectives [24,25]. Additionally, the synthetic records can be used in lieu of or in conjunction with recorded accelerograms to perform ground motion selection. The impact of ground motion selection criteria specified in ASCE/SEI 7-16 [26] and Eurocode 8 (EC8) [27] on estimating seismic demand for masonry structures using both real and simulated datasets was explored by Karimzadeh et al. [28].

The main objective of this study is to analyse the seismic performance of conventional masonry constructions situated on Faial Island, a part of the Azores Plateau in Portugal. To accomplish this, synthetic acceleration time series will be utilised. The stochastic finite-fault method based on a dynamic corner frequency approach is employed to obtain region-specific records. Then, sets of records are selected covering the distribution of Peak Ground Acceleration (PGA) for various scenario earthquakes. Non-linear numerical models are utilised to calculate the capacity of building structures using a probabilistic performance-based seismic approach. Capacity curves are obtained for various seismic scenarios to evaluate the seismic performance of the structures. The numerical findings indicate that the structures are highly susceptible to moderate to extensive damage when subjected to large-magnitude events.

## 2 SIMULATED GROUND MOTION DATASET IN THE STUDY AREA

The present study focuses on the Azores Plateau in Portugal as the study area for constructing a ground motion dataset. This region is dominated tectonically by the Azores triple junction between the North American plate, the Eurasian plate, and the African plate. The central and eastern parts of the plateau are characterised by a diffuse and complex deformation zone, which underwent shearing under a dextral trans-tensile regime. The study area comprises five islands, namely Faial, Pico, Sao Jorge, Terceira, and Graciosa [29]. The following sections describe the ground motion simulation methodology, input-model parameters, and the results obtained from the simulations.

### 2.1 Ground motion simulation methodology

The research employs the stochastic finite-fault ground motion simulation methodology of Atkinson and Assatourians [30], implemented using the EXSIM12 platform [31], to model the acceleration time series of the scenario events. The simulation algorithm, proposed by Motazedian and Atkinson [32] and based on the original FINSIM code by Beresnev and Atkinson [33], is enhanced by incorporating improvements suggested by Boore [34]. This approach considers various factors such as earthquake magnitude, fault geometry, slip distribution, density, rupture velocity, and strike to identify the fault rupture. The method combines the source contribution with attenuation parameters and site effects to obtain the seismic signal in the time domain at any observation site.

In the stochastic finite-fault method, the ruptured fault plane is divided into smaller sub-sources represented as a grid, with each sub-source assumed to be a point-source with a $\omega^{-2}$ source spectrum, as proposed by Boore [35,36]. The sub-sources rupture with a time delay that depends on their distance from the hypocentre, and the time domain summation of the contributions from the delayed sub-sources is carried out to obtain the final ground motion simulation as follows:

$$A(t)=\sum_{i=1}^{N} H_i Y_i\left(t+\Delta t_i+T_i\right) \quad 1$$

where $A(t)$ represents the total seismic signal at a specific time $t$, $N$ refers to the total number of sub-sources, $Y_i$ indicates the seismic signal of ith sub-source, which is calculated by performing the inverse Fourier transform of the $i^{th}$ sub-source spectrum [34,36]. The value $\Delta t_i$ is calculated by adding the time delay due to the distance of the $i^{th}$ sub-source from the hypocentre to the time of fracture initiation. The term $T_i$ denotes a fraction of rise time considered for additional randomisation. In contrast, the term $H_i$ represents the normalisation factor of the $i^{th}$ sub-source, which is introduced for energy conservation. The equation for $H_i$ is given as follows:

$$H_i=\frac{M_0}{M_{0i}}\sqrt{\sum_j\left(\frac{f_0^2 f_j^2}{f_0^2+f_j^2}\right)^2 \Big/ N\sum_j\left(\frac{f_{0i}^2 f_j^2}{f_{0i}^2+f_j^2}\right)^2} \quad 2$$

where, the symbol $f_0$ represents the corner frequency of the primary fault plane, $f_j$ corresponds to the $j^{th}$ frequency ordinate. $M_0$ denotes the total seismic moment, and the terms $M_{0i}$ and $f_{0i}$ signify the seismic moment and corner frequency, respectively, of the $i^{th}$ sub-source. The expressions for $M_0$ and $f_{0i}$ are given below:

$$M_{0i}=\frac{M_0\times S_i}{\sum_{i=1}^{N} S_i} \quad 3$$

$$f_{0i}=4.9\times10^6\beta_s\left(\frac{\Delta\sigma}{p\times M_0}\right)^{\frac{1}{3}} \text{ where } p=\begin{cases}\frac{N_R}{N} & \text{if } N_R \prec N\times PP\\ PP & \text{if } N_R\geq N\times PP\end{cases} \quad 4$$

where $s_i$ denotes the slip of the $i^{th}$ sub-source in Equation 3. In Equation 4, the term $N_R$ represents the total number of sub-sources that become active when the $i^{th}$ sub-source is triggered, and $\Delta\sigma$ denotes the stress drop in bars. The term PP is the pulsing percentage. The algorithm employs a dynamic corner frequency approach where the corner frequencies of the activated sub-sources decrease as the rupture progresses until it reaches a predefined level of PP. In contrast, the corner frequency of the remaining sub-sources remains constant.

## 2.2 Information on the simulations

In this study, a set of 23 scenario events featuring varying magnitudes ranging from 5.0 to 6.8 with a bin size of 0.1 are simulated on ruptured fault planes. All simulations are performed in the bedrock. To calibrate the simulation parameters for these events, region-specific input-model parameters provided by Karimzadeh and Lourenco [37], based on simulation validations against observed motions from the 1998 Faial (Mw=6.2) event, are employed. However, to account for the uncertainty associated with the parameters representing source and attenuation effects, key parameters such as hypocentre location, stress drop, pulsing percent, quality factor, and kappa are treated as random variables. Regional models with probability distribution functions and their ranges are implemented using the study by Carvalho et al. [38]. For every event, 30 Monte Carlo simulations are performed, each with distinct combinations of input parameters. The study area, depicting the tectonic plates and stations utilised for the simulations, is presented in Figure 1. The simulations are conducted at 359 nodes on bedrock, as indicated by the triangular symbols in Figure 1.

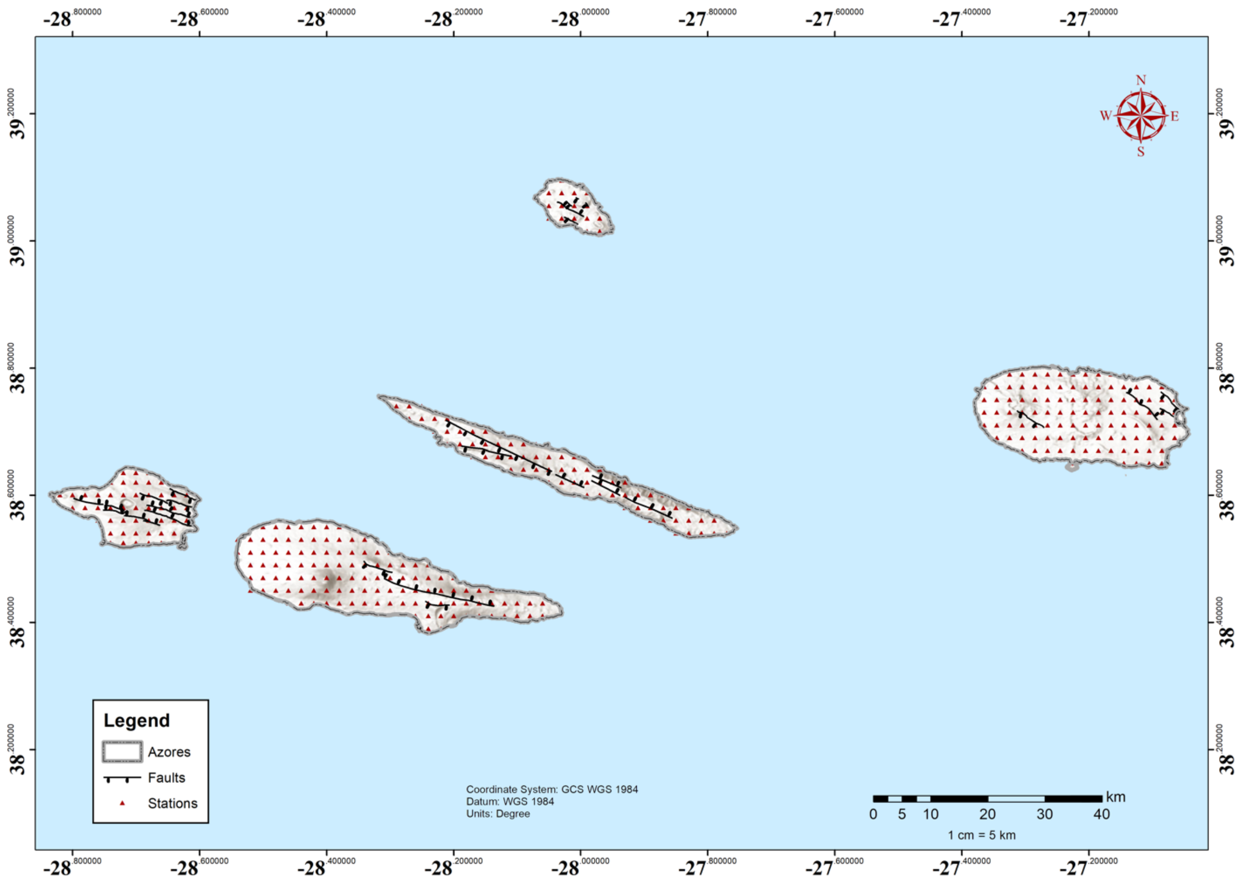



Figure 1 Study area illustrating the tectonic plates, with triangular symbols denoting the stations utilised for ground motion simulations.

### 2.3 Results of simulations

The 5% damped Pseudo Spectral acceleration (PSa) values of the simulated dataset are computed for randomly selected stations located in the centre of each island. These computations are performed for the scenario event with the largest magnitude (Mw=6.8) and the resulting PSa values are plotted in Figure 2. The figure provides a comprehensive representation of the PSa values at each station, including the individual, mean, median, standard deviation (std), minimum (min), and maximum (max) values for all simulations. This information is useful in providing a clear understanding of the variability in the dataset and the potential range of PSa values that could be observed at each station. The range of probable spectral values demonstrated by the plotted PSa values serves as evidence of the stochastic behaviour of the dataset.

(a) (b)

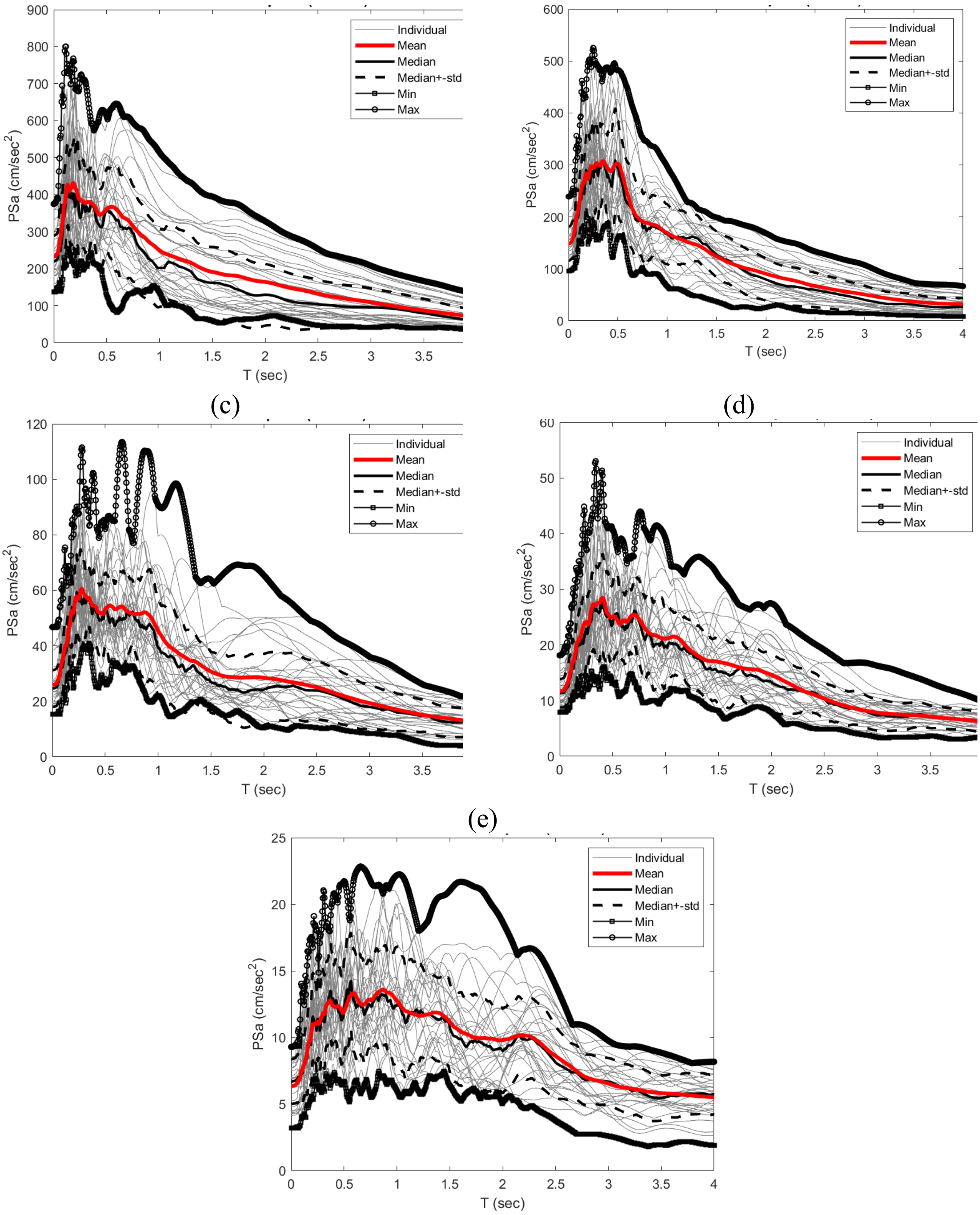
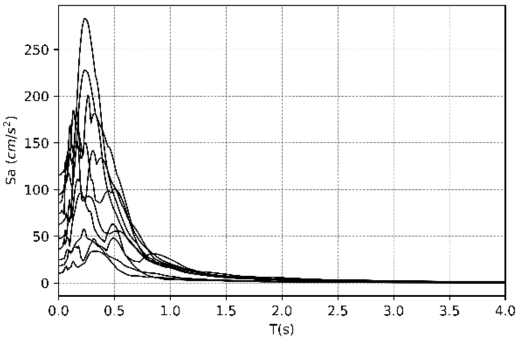


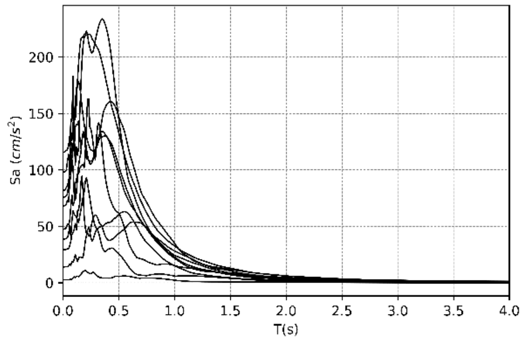

Figure 2. 5% damped PSa for stations in the centre of Azores islands, including (a) Faial, (b) Pico, (c) Sao Jorge, (d) Graciosa, and (e) Terceira.

## 3 GROUND MOTION SELECTION APPROACH

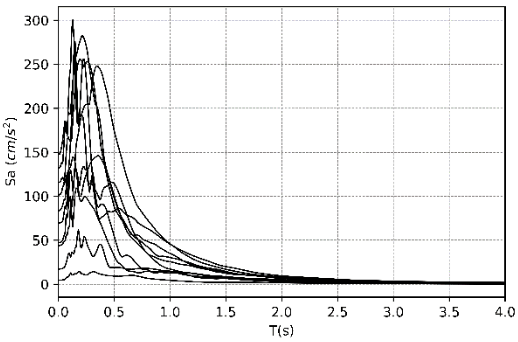
Various sets of simulated records are selected considering Mw values of 5.0, 5.1, 5.2, 5.5, 5.6, 5.8, 6.0, 6.2, 6.4, and 6.6. In this regard, each suite of records corresponds to a specific value of Mw, and 10 records within the set are selected to cover the PGA dispersion for each scenario earthquake. Figure 3 shows the acceleration response spectra (Sa) of the 10 sets of the selected records, covering the distribution of PGA for each scenario earthquake.



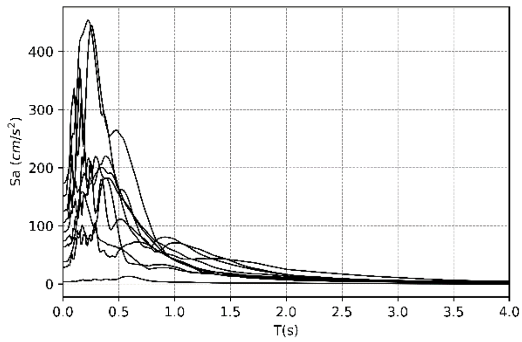

(a) Set 1, Mw = 5.0



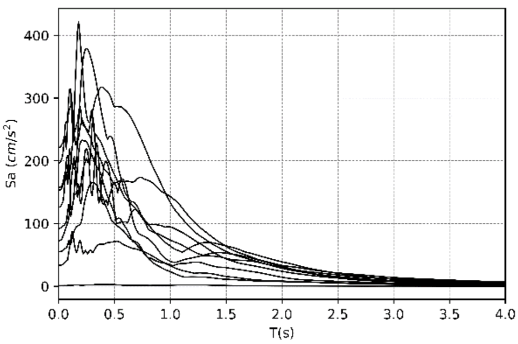

(b) Set 2, Mw = 5.1



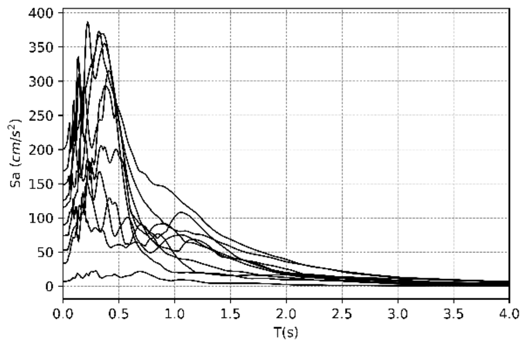

(c) Set 3, Mw = 5.2



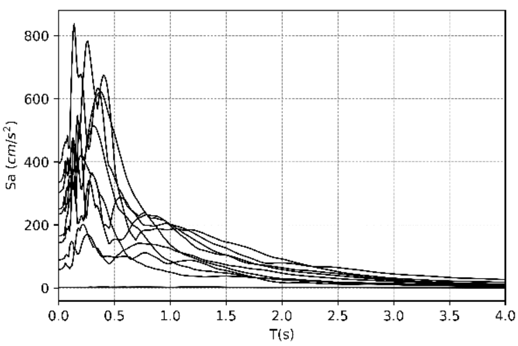

(d) Set 4, Mw = 5.5



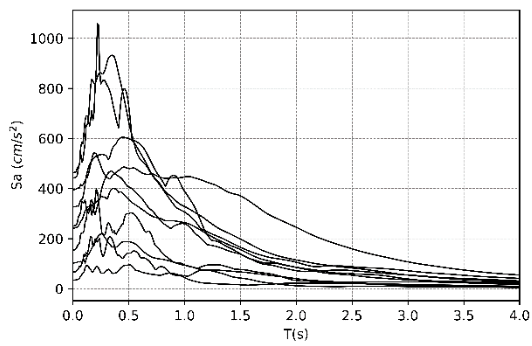

(e) Set 5, Mw = 5.6



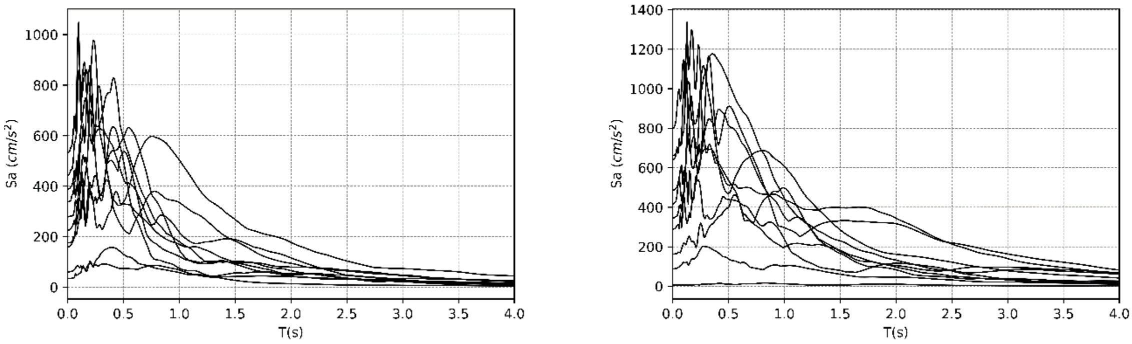

(f) Set 6, Mw = 5.8




(h) Set 7, Mw = 6.0




(i) Set 8, Mw = 6.2




(j) Set 9, Mw = 6.4 (k) Set 10, Mw = 6.6

Figure 3. Sets of record for each scenario earthquake.

# 4 STRUCTURAL CAPACITY AND SEISMIC RESPONSE

## 4.1 Building typology and numerical modelling

One of the most traditional building typologies in Fail is characterised by rubble stone masonry walls and flexible timber floors, representing more than 50% of the building stock in that region.

In the scope of the present study, a representative URM building typology of Azores with three stories high and rectangular plan (7.5 m x 12.0 m) is used for the subsequent analysis. Details regarding the geometry parameters and material properties can be found in Bernardo et al. [39] and Costa [40].

The tridimensional numerical model of the buildings was developed using an equivalent frame modelling strategy where the in-plane behaviour only governs the capacity. Some of the model's features include the accurate representation of the principal in-plane failure mechanism, including the stiffness and strength degradation, such as bending rocking, diagonal shear and sliding. Further details regarding the modelling formulation can be consulted by Penna et al. [41].

Figure 4 depicts the numerical model considered for the subsequent analysis.

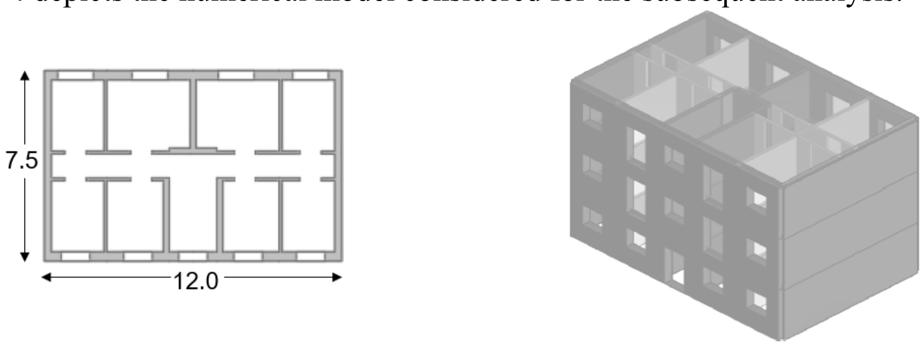



Figure 4. Typology layout and 3D-model considered.

## 4.2 Limit states and seismic assessment

The capacity curve is computed using nonlinear static analyses with a load pattern proportional to the damage (adaptive pushover). Then, the seismic performance is obtained for different spectra using the improved Capacity Spectrum Method [42] and considering the median of 10 PSa in each scenario.

The Damage States (DSs) considered in the present study for the seismic assessment are defined at a global scale in the capacity curves as a function of the yielding (Sdy) and ultimate displacement (Sdu). The ultimate displacement is considered a 20% decay of the maximum shear strength, while the yielding displacement corresponds to the immediate occupancy. The limit states adopted are summarised in Table 1 [42].

Table 1 – Damage states adopted.

| Limit state | Description | Global scale |
|---|---|---|
| DS1 (slight) | Appearance of diagonal hairline cracks in the walls' surface and parapets, being larger around openings. | 0.7*Sdy |
| DS2 (moderate) | Diagonal cracks and large cracks around the parapets. Element's separation. | Sdy |
| DS3 (severe) | Extensive cracking and relative movements to their supports. Some masonry may have fallen. | Sd (Sa,max) |
| DS4 (extensive) | Near to collapse due to in-plane of the walls. | Sdu = Sd (0.80*Sa,max) |

Figure 5 shows the capacity curve with the limit states considered and the seismic performance for different scenarios. As can be seen, the Mw=5.0 and Mw=5.2 produce performance values lower than the DS1, while the Mw =5.5 almost reaches DS1. For Mw =5.8, the performance is above DS2. Finally, for Mw =6.0 and 6.2, the expected performance reaches DS3, where the latter is slightly getting closer to DS4. Note that the results discussed assume a deterministic capacity for the buildings, and the uncertainty in the seismic scenario is not addressed. Thus, further studies are needed in a probabilistic seismic assessment framework.

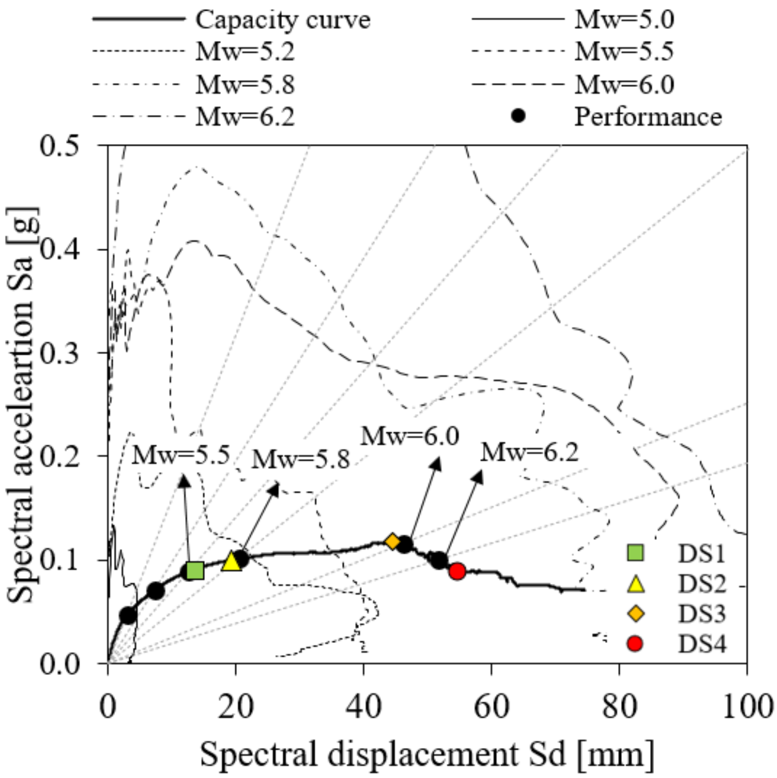


Figure 5. Seismic performance of the structure.

## 5 CONCLUSIONS

The evaluation of the seismic performance of topological masonry buildings using ground motions simulations after the 1998 Faial (Mw=6.2) earthquake is addressed in this study. The simulations are generated using the stochastic finite-fault method for region-specific scenario earthquakes in the Azores Plateau at bedrock. The stochastic behaviour of input-model parameters is considered regarding source and path attenuation effects. The dataset comprised a wide range of moment magnitude and source-to-site distance due to the rupture of active faults in the Azores Plateau. Additionally, the numerical structural model consists of a representative URM building typology of the Azores region, which is developed using an equivalent frame modelling strategy where the in-plane behaviour only governs the capacity.

Ground motion simulations offer a substantial benefit by capturing the random characteristics of earthquakes, as they provide a more precise depiction of potential seismic hazards. This enables informed decision-making in terms of seismic risk management and mitigation strategies. Regarding the numerical results on the seismic response and structural capacity, the structural system exhibited performance levels up to moderate damage for scenarios with Mw ≤5.8, while for scenarios with larger magnitudes (Mw=6.0 and 6.2), the expected performance reaches from severe up to extensive damage. These results demonstrate the vulnerability of typological URM buildings in the Azores region to seismic actions.

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