SEISMIC FRAGILITY ASSESSMENT OF HISTORICAL UNREINFORCED MASONRY BUILDING AGGREGATES

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Abstract: Past megathrust earthquakes in Central Chile, such as the 1985 Algarrobo (Mw 8.0) and the 2010 Maule (Mw 8.8) events, have exposed the high vulnerability of historical urban centers, which typically involve aggregates of unreinforced masonry (URM) structures. Their seismic response has proven to be rather complex due to the morphological features of the adjacent structural units that conform the aggregate, the irregularities in height and plan configurations, the various modifications undergone in time, the conservation state of the structures, the quality of element and unit connections, the existence of accumulated damage, among several other factors. These characteristics make the buildings particularly vulnerable to the activation of local failure modes. In this research, we compute the analytical seismic fragility of 423 URM buildings within 21 urban aggregates in the historic neighborhood of Yungay in Santiago, Chile. The well-known *Failure Mechanism Identification and Vulnerability Evaluation* method (FaMive), a mechanical approach based on limit-state analysis and failure modes was used to compute collapse load factors and derive capacity curves for each structure. This paper also introduces a new selection algorithm to automatically classify the capacity curves that uses an optimal logic tree (LTA). The algorithm automatically clusters the capacity curves into different classes of historical buildings. These FaMive results are then used to derive Analytical Fragility Functions (AFFs) for later use in risk assessment. The aim of this work is to provide the data to prioritize mitigation strategies that enable us to preserve better this particular heritage, as well as that of other similar historical urban areas in Chile and Latin American cities, which bear a strong architectural resemblance since their foundation.

1 General considerations

The 1985 Algarrobo (Mw 8.0) and 2010 Maule (Mw 8.8) earthquakes, which impacted the Central Valley of Chile, have shown the high vulnerability of the historic buildings in aggregation (HBA) of Chilean quarters and heritage centers, which mostly correspond to unreinforced masonry structures (Riddell et al, 1987; D'Ayala&Benzoni, 2012). In particular, the Maule earthquake was important in terms of loss of human life (more than 500 victims), economic loss (between 15-30 billion dollars) and destruction of infrastructure and housing (half a million homes were severely damaged) (ARCMT, 2011). Furthermore, 370,000 plain masonry heritage buildings were completely destroyed or irreparably damaged, 500,000 houses suffered severe structural damage and more than 200,000 families lost their homes (Gobierno, 2013). From an economic perspective, the damage to the built heritage resulted in a significant cost to the State, since 52% of the country's Historic Monuments and Typical Zones suffered some degree of damage (CMN,2013). As a result of this earthquake, the National Council for Culture and the Arts created the Support Program for the Reconstruction of Tangible Heritage (2010), with the aim of restoring and consolidating the heritage properties considered valuable for the communities in the regions affected by the earthquake (CMN, 2013).

The magnitude of the social, material, and economic impact produced by this seismic event, evidenced the need to have and implement public policies oriented to the prevention and mitigation of the seismic risk, in particular of historic building aggregations.

To date, several strategies and methods have been applied to assess the seismic vulnerability of historic simple masonry structures in Chile. These analyses, however, have only been developed for buildings recognized as National Monuments (churches, palaces, etc.), leaving aside historic buildings in aggregation. Most studies have focused their attention on the seismic performance of monuments that constitute individual structural units, and the evaluation of the vulnerability of HBA formed by aggregate structural units (i.e., urban blocks that do not correspond to a political-administrative division), such as houses and ordinary buildings, are very scarce (Santa María et al., 2017; and Palazzi et al., 2022). The HBAs of Chilean quarters and historic centers are a large and important part of the national cultural heritage, since they form "living human settlements, strongly conditioned by a physical structure coming from the past and recognizable as representative of the evolution and identity of a people" (UNESCO/PNUD, 1977).

In this context, fragility assessment and risk analysis of HBAs become essential tools for preventive planning and emergency management aimed at the protection and conservation of this heritage, contributing to the mitigation of human and socioeconomic losses caused by future seismic events.

The field of application of the study will be the Yungay quarter, declared a *Typical Zone* by the CMN as a heritage landmark of the city of Santiago. Therefore, this research focuses on the simulation and evaluation of the seismic behavior of HBAs in this neighborhood, including houses and ordinary buildings, which are part of structural aggregates (urban blocks) of Santiago's pericenter-but common to many other cities in the Chilean territory-with the objective of foreseeing and typifying damages, and translating these learnings into valuable inputs for public policies of prevention and conservation of this heritage.

2 Brief state of the art

In the last twenty years, much research has significantly contributed to the assessment of the seismic vulnerability of existing buildings, as summarized in Rossetto et al. (2013) y D'Ayala et al., (2015). Commonly used methodologies for the analysis of historic city centers are of the empirical type. The first predictions in this field were based on the observation of post-earthquake damage scenarios, through the derivation of Damage Probability Matrices, DPMs (Whitman et al. 1973; Braga et al. 1982), which expresses in a discrete form the probability that the *k-th* element (of an entire structure and/or macroelement in the case of simple masonry structures) reaches a given damage level Dk=j, conditioned to a seismic intensity IM. From the results obtained by means of DPMs, different techniques have been proposed to derive fragility curves (Orsini 1999; Martinelli et al.2008; Rossetto et al., 2013). Another empirical approach currently widely used in the assessment of HBA vulnerabilities - originally developed by Benedetti et al. (1988) and then adapted and applied to various architectural typologies - consists of quantifying a vulnerability index (VI) based on the scoring and weighting of a number of parameters considered influential in determining the propensity to seismic damage of specific types of buildings. These methods have the advantage of delivering fragility functions, correlating a seismic intensity measure (such as the European Macroseismic Scale (EMS-98), Modified Mercalli (MMI), or Peak Ground Acceleration (PGA)) to the median damage suffered by a building, using the binomial or lognormal distribution. However, each application needs a calibration depending on the local geomorphology and seismology, which is difficult to achieve in the absence of pre-existing seismic damage data, making these calibrations heavily dependent on expert opinion.

Analytical vulnerability assessment methods overcome these limitations, being more versatile in their applicability; however, they require more data and computational effort. In particular, analytical methods based on the evaluation of local collapse mechanisms and on capacity or displacement spectra allow the analysis of a large number of buildings, through a reduced number of parameters and simple structural models. The methods based on the evaluation of collapse mechanisms (Bernardini et al. 1990; D'Ayala and Speranza 2003, Donà et al. 2021) simplify the structure into large subcomponents for which the possible local failure modes can be identified and the collapse load factors, representing the lateral resistance capacity of the structure, are calculated. Additionally, capacity or displacement spectrum-based methods (Ahmad et al. 2010; Irizarry et al. 2011) use simplified mechanical models to obtain capacity curves on the basis of which elastic and ultimate strength and displacement thresholds can be identified to determine yield and damage states (D ' Ayala et al. 2015). When applied to large sets of buildings and/or considering a large number of alternative seismic spectra, the calculated results can be treated statistically to obtain fragility and vulnerability functions (D ' Ayala et al. 2015).

In the field of seismic behavior assessment of buildings in aggregation in historic urban centers, considering the sample size and the level of detail required for a complete and comprehensive structural characterization, a nonlinear dynamic analysis of each building would not be possible or feasible. Therefore, in this research with the purpose of simulating the seismic behavior of the HBA part of urban blocks of the Yungay quarter, the well-known Failure Mechanism Identification and Vulnerability Assessment (FaMIVE, D'Ayala and Speranza 2003) method was used, a procedure based on the estimation of possible local collapse mechanisms - specifically developed for the evaluation of historic urban centers - considering in-plane and out-of-plane failure modes. The FAMIVE method allows the derivation of capacity curves and fragility functions based on ultimate lateral resistance capacity and elastic and ultimate displacements (Fajfar and Dolsek 2012). For this purpose, an adapted version of the N2 method was used, which considers a tetralinear capacity curve, rather than a simple bilinear one, as well as the use of a suite of response spectra obtained from natural records, instead of a design code response spectrum. Moreover, out-of-plane mechanisms were explicitly considered for structures without rigid diaphragms, which show more flexibility a less ductility.

2.1 Selected method for vulnerability assessment of HBAs: FaMIVE

FaMIVE (D'Ayala et al., 2008) was born from the systematic collection of post-earthquake damage suffered by historic buildings in unreinforced masonry in different seismic contexts, which led to identify a set of 23 recurrent failure modes for HBA structures, both in-plane and out-of-plane. Each identified collapse mechanism corresponds to different constraints between the façade and the rest of the structure; therefore, a single collapse mechanism can be defined, and its collapse load multiplier can be calculated given its geometric and structural characteristics, and the types of constraints. An exhaustive and detailed explanation of the method is given in D'Ayala, (2013).

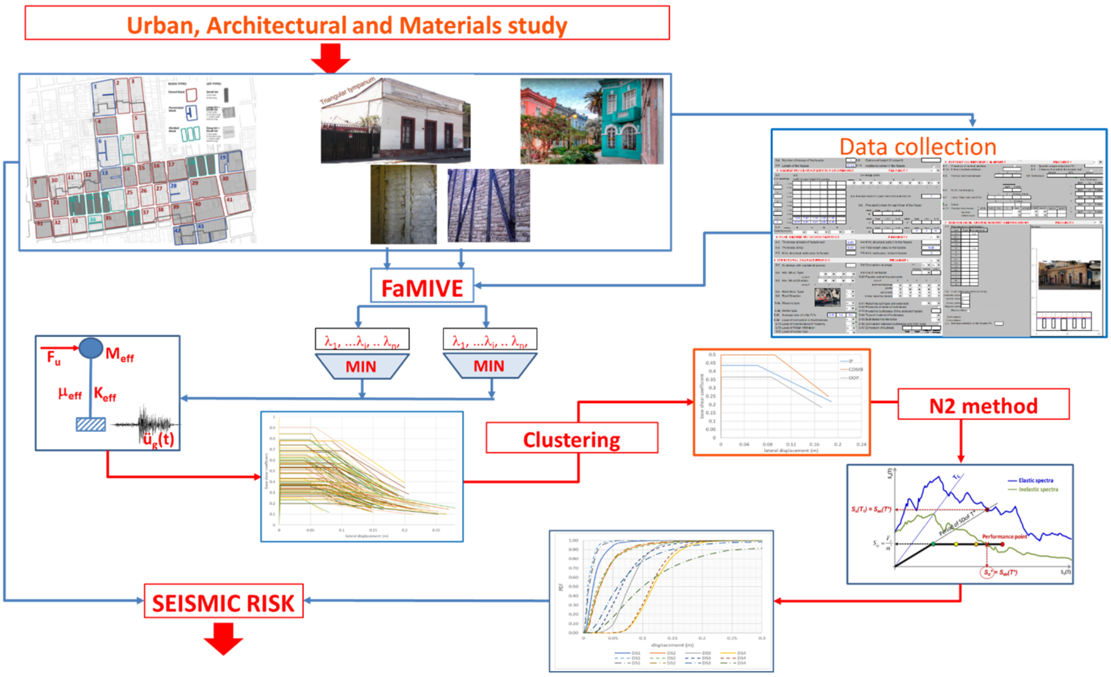

Figure 1. Steps of FaMive methodology.

To choose the most critical failure mode leading to the highest possible loss (i.e., the most vulnerable condition for the façade or building), the method provides for each failure mode the collapse multiplier of the mass of walls and floors involved in the mechanism. The characteristics of the identified mechanism are then used to derive a single-degree-of-freedom equivalent nonlinear capacity curve (SDOF) which, when compared to a seismic demand, allows the yield point to be identified. The FaMIVE methodology is schematically illustrated in the diagram in Fig. 1. The collapse load multiplier (λi) for the i-th failure mode is interpreted as proportional to the lateral acceleration capacity of the structure required to activate such mechanism. Therefore, the fragility curves in terms of lateral acceleration capacity can be derived directly.
Finally, having defined an equivalent nonlinear SDOF and its representative capacity curve, as defined in D'Ayala, (2013), four damage limit states are calculated, corresponding to limited damage (DL), structural damage (SD), near collapse (NC) and collapse (C), respectively. Further details on the derivation of the capacity curves and the calculation of the limit states are provided in D'Ayala, (2013).

3 Seismic Vulnerability of the Yungay Quarter

The Yungay quarter located in the western area of the historic center of the capital of Chile is one of the most representative typical Zones of Santiago, according to the declarations issued by the National Monuments Council (CMN) through Law N° 17,288, Supreme Decrees No. 217 (2000), N° 43 (2009), and N° 13 (2019).

At the beginning of the 19th century, the area of Yungay, called *Quinta de los Portales,* was made up of agricultural land. President José Joaquín Prieto (1831-1841) founded the quarter on January 20, 1839, to commemorate the triumph of the final battle of the war against the Peruvian-Bolivian Confederacy, the Battle of Yungay. Between 1836 and 1873, the new republican quarter was planned by engineers Jacinto Cueto and Juan de la Cruz Sotomayor following the pattern of the foundational grid, with larger rectangular urban blocks. Fig.2a shows the current location and Fig.2b the urban configuration of the quarter.

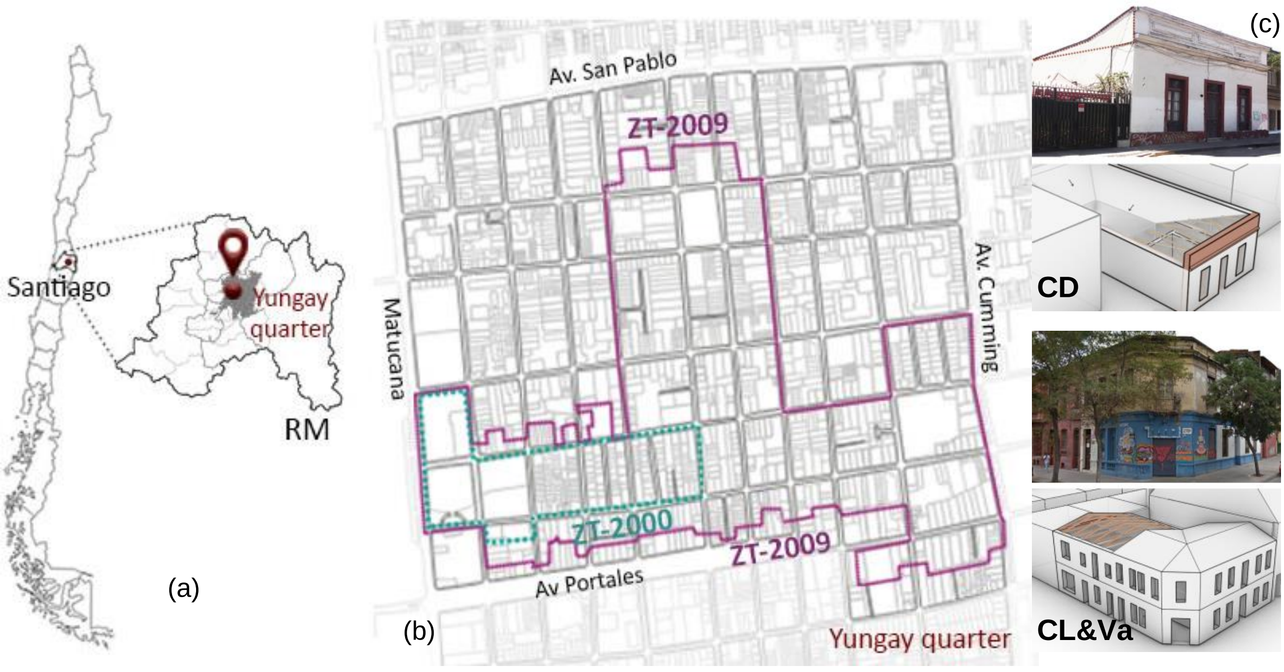

Figure 2. Case study: (a) Yungay quarter localization; (b) urban configuration; and (c) historic architectural typologies of Yungay: Colonial Derivation architectures (CD) and Clasicist & Variant buildings (CL&Va).

Currently, according to the WHE-PAGER Taxonomy defined by Jaiswal and D'Ayala (2011), the Yungay *Typical Zone*'s HBAs (Decree No. 43, 2009) can be classified into buildings of: (a) adobe masonry with mud mortar, wooden roof and floor (Type A1, corresponding to 30% of the historic structures); (b) unreinforced brick masonry with lime mortar, wooden roof and floor (Type UFB3, corresponding to 11%); (c) adobe-like, wood framing with earth blocks (Type MMA, corresponding to 5%); and (d) wood framing with brick masonry infill (TYPE MMB, corresponding to 11%).

Recent research on historic buildings in the neighborhood (Palazzi et al., 2022) detected that 60% of HBAs are one- or (rarely) two-story continuous façade properties with an elongated floor plan that includes a rear courtyard, north-south or east-west orientation, and a roof structure composed of single- or double-gabled wood trusses. This general distribution is defined as colonial derivation (CD) style and includes *Popular Classicism* and *Republican architecture* (Fig. 2c).

On the other hand, it was detected that about 40% of HBAs are 2-story structures (rarely 3 or 4 stories), a variant of the colonial continuous façade typology with a rectangular and elongated planimetric conformation (10-12 m wide and 50-60 m long), oriented north-south or east-west, with one or two patios at the back, with walls of the ground floors of adobe or brick, and with the upper floors being characterized by mixed wood-masonry construction techniques of adobe or brick, and a roof structure composed of wooden single- or double- gabled trusses with collar beams. These structures, introduced in the mid-19th and early 20th centuries, are defined as *Classical* style and *Variants* (CL&Va) (Fig. 2c) and include Neoclassical, Neo-Baroque and other eclectic stylistic expressions

3.1 Construction of the database

The Yungay *Typical Zone*, whose perimeter is established by the Supreme Decree N° 43 (2009), includes 43 urban blocks and a total of 542 historic buildings, each composed of 1, 2 or 3 façades according to its position in the building aggregation, i.e., building contiguous to two adjacent ones (1 façade), corner building (2 façades) or octagonal corner building (3 façades). Therefore, considering the size of the HBA population and the level of detail required for its complete and exhaustive structural characterization, a representative sample of façades to be analyzed was identified, according to the following criteria (Table 1):

(i) type of block and urban lots;

(ii) level of alteration of the block with respect to its original form.

According to the morphological characteristics of the area (analyzed in detail in Palazzi et al, 2022) in Yungay we can identify four types of blocks:

- Closed [C]: traditional urban model of the foundational city with contiguously organized façades. In the typical zone, there are 29 blocks [C], characterized by a heterogeneous set of structural units (UE), generally built at different times with or without a solution of continuity, composed by elongated rectangular shape. Adjacent UE are interconnected with more or less structurally effective connections, depending on their evolutionary process.
- Penetrated [P]: they originate from the alteration of a closed block, due to the introduction of Cités (at the beginning of the 20th century). The Cités (tenements) are groups of aggregated dwellings that occupy and fragment a single deep lot with several social dwellings organized around a central or lateral alley (1.5 m to 6 m wide). In the typical Yungay Zone, there are 8 penetrated blocks and 10 Cités.
- Divided [D]: they consist of the decomposition of a block closed by one or two streets, in two or three divided blocks. In Yungay there are 4 split blocks. Although the formers are generally built of brick masonry, the latter are urban blocks completely reconstructed in confined masonry.
- Mixed, split-penetrated [P-D]. Two blocks [P-D] are identified. Due to their architectural qualities, these were the first Yungay's urban blocks to be declared a typical zone through Decree No 217, 2000.

Due to the deep and constant process of urban growth that has characterized the quarter since its foundation, the Yungay quarter is composed of heterogeneous aggregate buildings (considering architectural, constructive and structural characteristics) that, because of remodeling of internal spaces, enlargements and additions of new floors, present important structural discontinuities. These alterations of the architectural and structural morphology of the original blocks have direct implications on the seismic behavior of the added structures in simple masonry, leading to an increased risk of out-of-plane mechanisms due to poor connections between walls or parts of the building. In this context, three levels of block alteration are identified: (i) low level of alteration (less than 30% of the original block structure); (ii) medium level of alteration (between 30% and 70%), and (iii) high level of alteration (greater than 70%).

Once the representative sample of quarter blocks to be analyzed was identified (21 blocks out of 43 as total, as shown in Table 1), with the objective of developing a comprehensive database to evaluate the seismic fragility of the constituent HBAs, 423 historic façades were individually inspected over a period of three months.

Table 1. Representative sample of Yungay neighborhood`s urban blocks, considering the type of block-lot and the level of alteration of the original block.

Type of urban block	**Closed**		**Penetrated**		**Divided**		**Mixted**
Nivel of alteration							
< 30%	-	25, 11	-	6, 34	-	7	-
between 30-70%	12, 36	2, 33	13, 42	1, 28	36	-	22, 24
≤ 70%	4, 16	-	19, 43	-	23	-	-

A team of three restoration architects and two engineers were trained to collect the data through the FaMIVE inspection form, where it was possible to identify 6 sections related to different characteristics of the structural unit analyzed: 1) urban (i.e., position of the façade in the block, number of connections of the façade with adjacent structures, type of soil etc.); 2) geometry of the façade; 3) geometry of the openings; 4) geometry of the floors; 5) structural (i.e., mechanical characteristics of the materials that constitute the structure, quality level of the connections, state of conservation, direction of the floor-to-ceiling beams with respect to the façade analyzed, etc.); and 6) additional vulnerabilities (i.e., para-roofs, chimneys, etc.).

A total of 423 files were implemented in a spreadsheet linked to an algorithm written in Visual Basic to run the limit state and collapse mechanism analyses, and obtain capacity curves for each structural unit.

3.2 Identification of possible collapse mechanisms

By means of the collected database, and using limit analyses with a kinematic approach for each façade—given the constraints, geometry, materials and loading conditions—the most probable collapse mechanisms, out of the 23 possible ones, were identified (Fig.3, D 'Ayala and Speranza 2003) by considering the out-of-plane, in-plane, and combined failure ones. Collapse load multipliers (λi) were calculated for each possible failure mode, and the most critical collapse mechanism was identified for each façade.

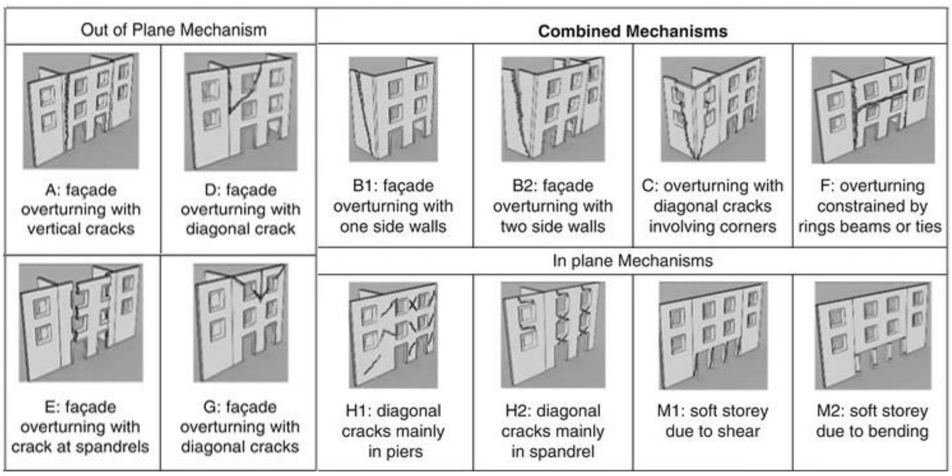

Fig. 3 - Abaco FaMIVE of collapse mechanisms for EHA buildings (D'Ayala and Speranza 2003)

The results of the FaMIVE analysis (Fig.4) show that the critical collapse mechanisms in Yungay, i.e., those that could be activated more frequently in the analyzed sample, are the out-of-plane mechanisms (which could be activated in 61% of the HABs analyzed). In particular, types A (16%) and E (80%) failures are the most common. Less frequent are the in-plane (19%) and combined (20%) mechanisms. These results are consistent with post-earthquake damage observations made in Yungay after the 2010 Maule earthquake (Palazzi et al., 2022), which confirm that out-of-plane mechanisms were the most frequent -associated at the major damage level (D4-D5)- in particular the type E fault activated in 38% of the historic buildings in the neighborhood.

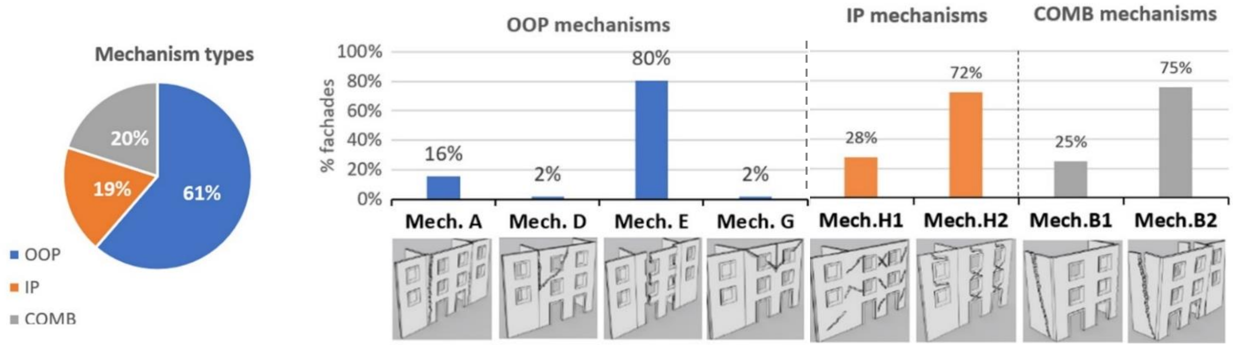

Fig. 4 - Identification of critical collapse mechanisms for the analyzed sample

3.3 Derivation of capacity curves and fragility analysis

The characteristics of the critical mechanisms identified were used to derive an equivalent nonlinear capacity curve of a single-degree-of-freedom oscillator (SDOF) to determine the drift at which different damage states are reached. The mass of the SDOF oscillator was determined by considering the volume of the facade and the tributary area of the horizontal structures involved in the mechanism; its stiffness from the geometry of the same portion, the type of mechanism and its constraints, using canonical stiffness equations for walls in lateral shear and bending deformation. The derived mass and stiffness were used to determine the fundamental T period of each oscillator. Finally, the ductility of the SDOF nonlinear oscillator was defined using a stability criterion, whereby the geometric parameters of the facade determine its loss of equilibrium (D'Ayala 2013; Novelli et al. 2015). Applying this procedure, linearized capacity curves corresponding to each facade were obtained, considering four damage limit states: limited damage (DL); structural element damage (SD), near collapse (NC) and collapse (C). Further details on the derivation of the capacity curves and the calculation of the limit states are provided in D'Ayala, (2013), but in general terms, capacity curve deformation limits are defined as those that produce a particular distribution of compression stresses, or that initiates the loss of vertical equilibrium. Whereas the damage limit states of the fragility functions correspond to predefined drift values, according to experimental and code reference ranges. Some examples of the capacity curves are presented next.

Fig. 5a shows the capacity curves obtained for the HBAs of the Yungay quarter: (UFB3), (A1), (MMA) and (MMB), identified in Section 3, while Fig. 5b presents the average capacity curves, obtained by grouping the facades that manifest the same propensity to damage, i.e., the critical failure mechanisms: E1, B1, B2, and E2. Finally, Fig. 5c shows the average capacity curves obtained by grouping facades showing critical mechanisms of the same nature: In Out-of-Plane Mechanism (OOP), failure involving the overturning of a facade poorly connected to orthogonal walls; Combined Mechanism (COMB), failure involving the overturning of facades well connected to orthogonal walls for them and poorly connected to horizontal structures; In-Plane Mechanism (IP), failure of facades well connected to transverse walls and horizontal structures.

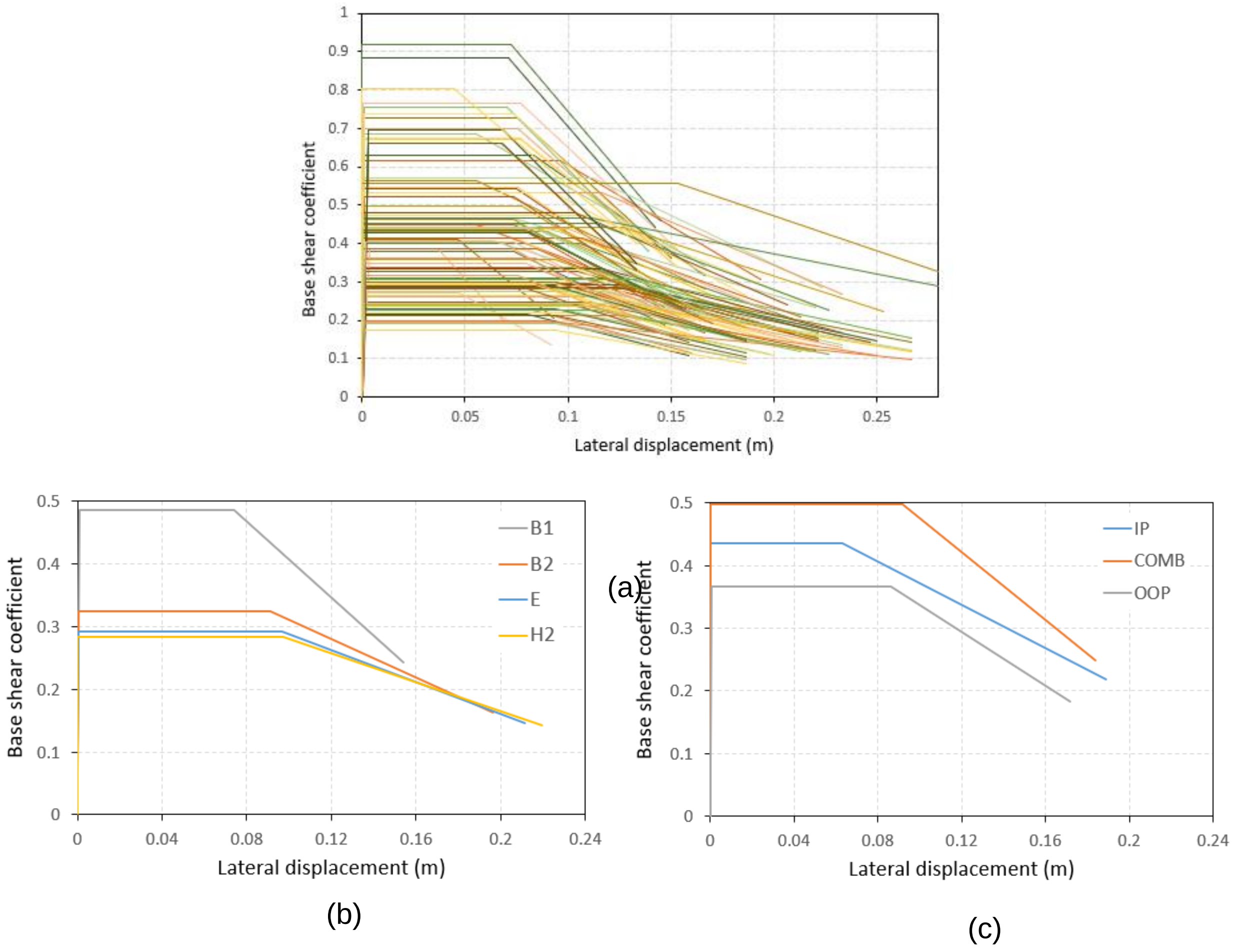

Fig. 5 – Capacity curves (a) of the 423 facades analyzed; (b) averages, obtained by grouping the facades that manifest the same critical mechanisms (B1, B2, E and H2), and (c) averages, obtained by grouping facades that manifest the same failure typologies (the in-plane IP, out-of-plane OOP, combined COMB).

3.4 Classification of capacity curves

Fragility curves are an input for seismic risk assessment, and ideally should be sufficiently general so it is possible to use them to study assets other than those considered for their computation, for instance, similar buildings in other regions of central Chile, or even alike structures in other Latin American countries. With this in mind, it is desirable to develop parametric fragility curves, so that the researcher may select the most adequate one for the set of buildings under study. For this purpose, the capacity curves were classified in clusters, based on their observable features such as architectural type, number of stories, material, presence of additions, roof type, orthogonal wall connection type, floor type, and different geometric metrics for the height, thickness, and surface area. The clustering was obtained through the use of a novel algorithm that produces an Optimal Logic Tree to classify the capacity curves, considering the observable features as decision variables. The obtained clusters are consistent in the sense that all capacity curves within a group are as similar as possible between them, and as different as possible from members of other groups.

For the classification process, each capacity curve is represented as a three-component vector $c = [A_u, \delta_u, \delta_c]$, where A_u is the value of the plateau acceleration, δ_u is the deformation at which the yield plateau ends, and δ_c is the post-yield deformation at which the acceleration reaches a value of $A_u/2$. While there are methodologies that would allow us to optimally classify the capacity curves in a cascading way [REF.], producing a decision tree, they are not adequate for out purposes, because these methods use the capacity curves vector-representation themselves for the classification process. This means that two different capacity curves could go into the same group just because they have similar values in the vector representation, but the similarity of the features of the facades would be completely ignored. Then, a group may have facades with different number of stories, material, etc; while two different groups may have elements that are very alike in terms of the facade features. The consequence of this is that the interpretability and generalization of the results would be lost because a researcher would not be able to simply perform a visual inspection of a new façade and predict its seismic behaviour (i.e., capacity curve). By enforcing the classification algorithm to use the façade features to classify the structures, it is possible to get the desired interpretable results in terms of mean and variance of the capacity curve parameters for different typologies of façades. The second reason why the existing methods are not adequate is because they work with numerical continuous variables, or at most with numerical integer variables, while in this case the façade features include numerical (both continuous and integer) values, and categorical values. Hence, a more general approach is required.

Details of the classification algorithm will be presented in an article soon to be submitted, but in general terms the procedure aims to minimize the variance of a cluster and branches the Logic Tree using the observable features following a cascading strategy. The resulting tree may be asymmetric, thus if one branch has high variance while the other does not, the former may be further divided, while the latter stops its division earlier. The obtained results may be easily interpreted by a researcher, and consist of a stochastic representation of the capacity curve of each cluster, which is associated with a combination of observable features. A small example of the classification is presented in Fig. 6.

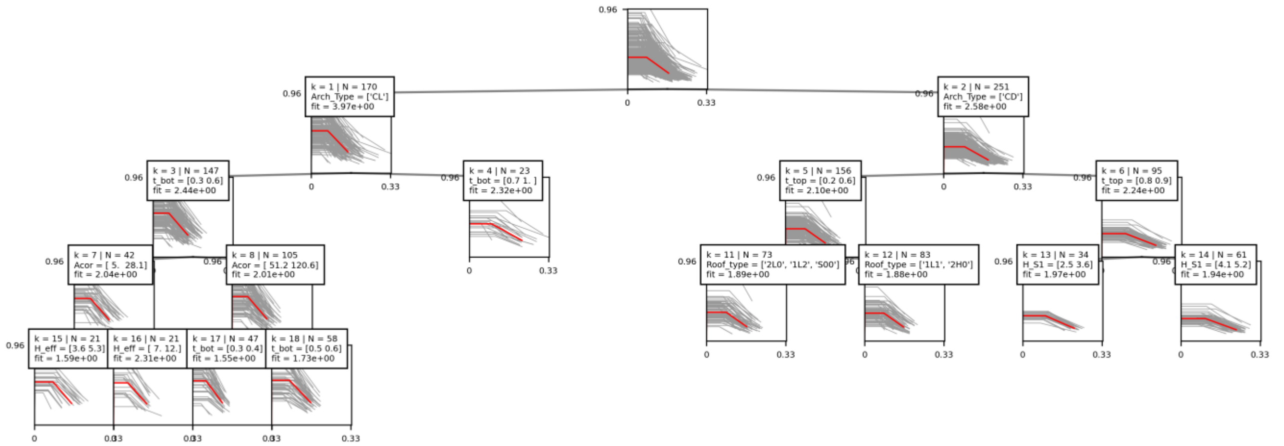

Fig.6 – Example of the classification of capacity curves

After the capacity curves were classified, the resulting median curves were used to obtain fragility curves for each cluster, following the FaMive methodology. Thus, a set of fragility curves was obtained for each of the clusters obtained before. An example of the fragility functions is presented in Fig. 7, which corresponds to a façade of cluster 0. The complete set of fragility functions will be presented in an article soon to be submitted.

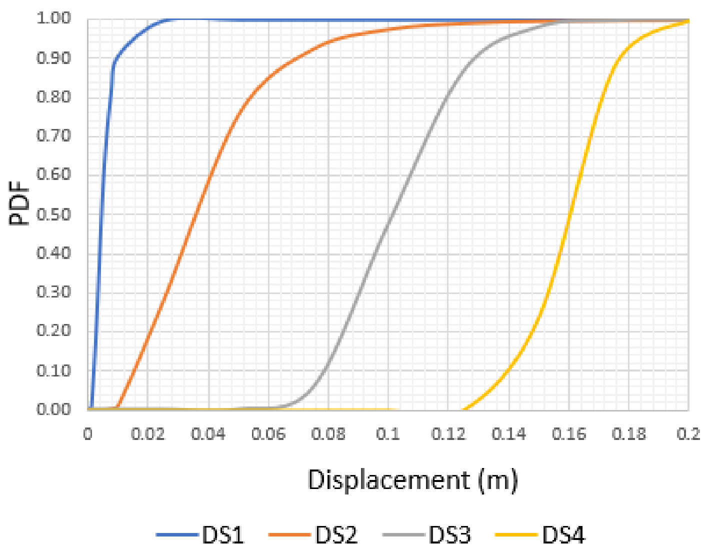

Fig.7 – Fragility curves

4 Conclusions

The limit state analysis with kinematic approach of 423 facades of the historic buildings in unreinforced masonry aggregation of the Yungay quarter was carried out, with the objective of evaluating their seismic capacity and propensity to damage under the action of future earthquakes. To this end, the FaMIVE methodology has been applied to characterize the structures by means of tetra-linear curves and a capacity spectrum approach adopted to calculate the yield point, using the design spectrum according to the current Chilean code NCh433Of96. Capacity curves were clustered using a novel algorithm that results in an Optimal Logic Tree, which classifies the curves based on their observable features. This gives the researcher easily interpretable results, which may be applied to similar buildings in other contexts. Finally, preliminary fragility curves have been derived for each of the façade clusters.

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6 References

Ahmad N, Crowley H, Pinho R, Ali Q (2010) Displacement-based earthquake loss assessment of masonry buildings in Mansehra City, Pakistan. J Earthquake Eng 14(sup1):1–37.

ARCMT, (2011). American Red Cross Multi-Disciplinary Team - Report on the 2010 Chilean earthquake and tsunami response. U.S. Geological Survey Open-File Report 2011-1053, v. 1.1, 68.

Benedetti D, Benzoni G, Parisi MA (1988) Seismic vulnerability and risk evaluation for old urban nuclei. Earthq Eng Struct Dynam 16:183–201

Bernardini A, Gori R, Modena C (1990) An application of coupled analytical models and experiential knowledge for seismic vulnerability analyses of masonry buildings. In: Koridze A (ed) Engineering aspects of earthquake phenomena, vol 3. Omega Scientific, Oxon, pp 161–180

Braga, F., Dolce, M., Liberatore, D. (1982). A statistical study on damaged buildings and ensuing review of the MSK-76 scale. In: Proceedings of 7th European conference on earthquake engineering, Athens, September

CEN (2005). *EN 1998-3:2005. Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings*, Comité Européen de Normalisation, Brussels.

Clough R.W., Penzien J. (1993). *Dynamics of Structures*, 2nd Ed., New York: McGraw-Hill Book Company

Consejo de Monumentos Nacionales - CMN (2013). Libro Reconstrucción Patrimonial En Chile 2010-2012, Publicaciones Cultura, Gob. de Chile.

D'Ayala D (2013) Assessing the seismic vulnerability of masonry buildings. Handbook of seismic risk analysis and management of civil infrastructure systems. Woodhead publishing, Sawston, pp 334–365

D'Ayala DF, Speranza E (2003) Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. Earthq Spectra 19(3):479–509

D'Ayala, D., Meslem, A., Vamvatsikos, D., Porter, K., Rossetto, T., Silva, V. (2015) GEM. Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings, Vulnerability Global Component Project https:// doi. org/ 10. 13117/ GEM. VULN- MOD. TR2014. 12

D'Ayala, D. and Benzoni, G., (2012). Historic and traditional structures during the 2010 Chile Earthquake: Observations, codes, and conservation strategies. Earthquake Spectra 28, No. S1, S425-S451

Dona M, Carpanese P, Follador V et al (2021) Mechanics-based fragility curves for Italian residential URM buildings. Bull Earthq Eng 19:3099–3127. https:// doi. org/ 10. 1007/ s10518- 020- 00928-7

Fajfar P, Dolšek M (2012) A practice-oriented estimation of the failure probability of building structures. Earthq Eng Struct Dyn 41:531–547. https:// doi. org/ 10. 1002/ eqe. 1143

Freeman S.A. (1998). The Capacity Spectrum Method as a tool for seismic design", *Proceedings of the 11th European Conference on Earthquake Engineering*, Paris, France.

Gobierno de Chile, Consejo Nacional de las Culturas y las Artes (2013). Reconstrucción Patrimonial en Chile 2010-2012. Santiago: Quad Graphics Ltda.

Irizarry J, Lantada N, Pujades LG, Barbat AH, Goula X, Susagna T, Roca A (2011) Ground-shaking scenarios and urban risk evaluation of Barcelona using the Risk-UE capacity spectrum-based method. Bull Earthq Eng 9:441–466.

Lagomarsino S, Giovinazzi S (2006) Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bull Earthq Eng 4:415–443

Mander J.B., Priestley M.J.N., Park R. (1988). Theoretical stress-strain model for confined concrete, *ASCE Journal of Structural Engineering*, 114(8): 1804-1826.

Martinelli, A., Cifani, G., Cialone, G., Corazza, L., Petracca, A. and Petrucci, G. (2008). Building vulnerability assessment and damage scenarios in Celano (Italy) using a quick survey data-based methodology, Soil Dynamics and Earthquake Engineering, 28, 875–889.

Novelli VI, D'Ayala D, Makhloufi N, Benouar D, Zekagh A (2015) A procedure for the identification of the seismic vulnerability at territorial scale. Application to the Casbah of Algiers. Bull Earthq Eng 13:177–202. https:// doi. org/ 10. 1007/ s10518- 014- 9666-1

Orsini, G, (1999) A model for buildings' vulnerability assessment using the parameterless scale of seismic intensity (PSI). Earthquake Spectra 15(3):463–483. doi:10.1193/1.1586053

Palazzi, N. C., Barrientos, M., Sandoval, C., & de la Llera, J. C. (2022). Seismic Vulnerability Assessment of the Yungay's Historic Urban Center in Santiago, Chile. Journal of Earthquake Engineering, 00(00), 1–28.

Riddell, R., Wood, S. L., & de la Llera, J. C. (1987). The 1985 Chile earthquake: structural characteristics and damage statistics for the building inventory in Viña del Mar. University of Illinois Engineering Experiment Station. College of Engineering. University of Illinois at Urbana-Champaign.

Rossetto, T, Ioannou, I, and Grant, D, (2013) Existing Empirical Vulnerability and Fragility Functions: Compendium and Guide for Selection, GEM Foundation, Pavia, Italy.

Santa María, H., Hube, M. A., Rivera, F., Yepes-Estrada, C., & Valcárcel, J. A. (2017). Development of national and local exposure models of residential structures in Chile. Natural Hazards, 86(S1), 55–79. https://doi.org/10.1007/s11069-016-2518-3

UNESCO/PNUD (1977) Conclusiones del coloquio sobre la preservación de los centros históricos ante el crecimiento de las ciudades contemporáneas, Quito, Ecuador

Whitman RV, Reed JW, Hong ST (1973). Earthquake damage probability matrices. In: Proceedings of the Fifth World conference on earthquake engineering