Lessons from the 2017 Central Mexico Earthquakes: the seismic performance of historic adobe buildings in the State of Morelos

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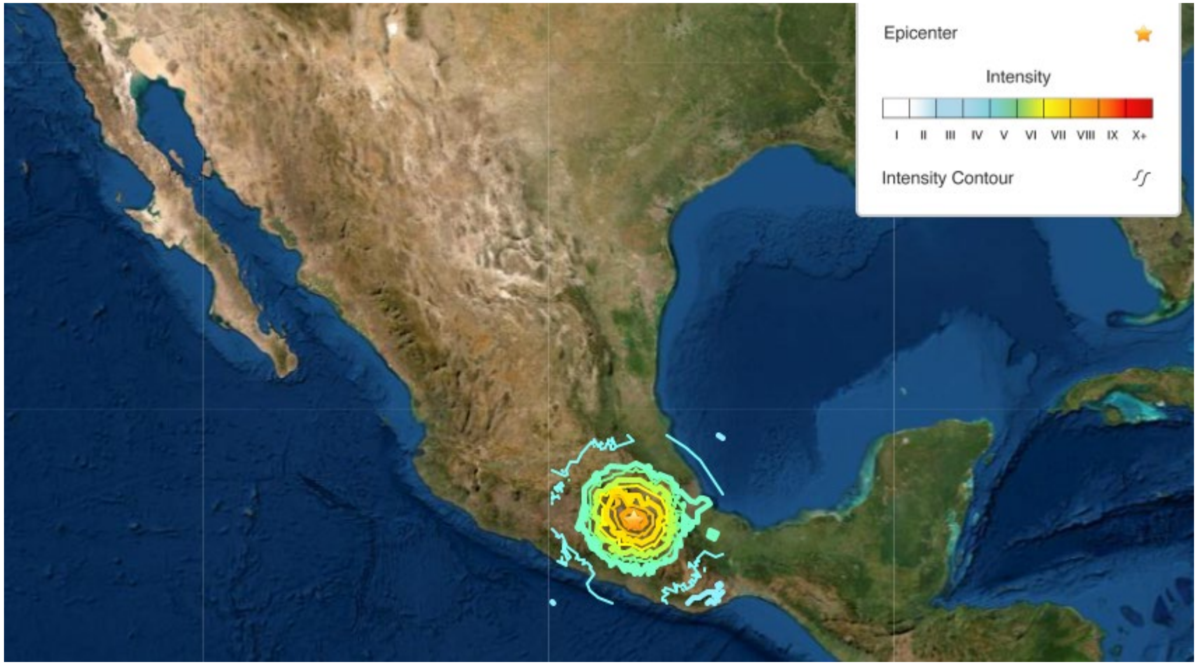
Background : the 2017 Puebla-Morelos Earthquake

In the 19th of September 2017, the so-called Puebla-Morelos Earthquake (Mw=7.1) hit the south-centre of the country. This event had its epicentre ca. 120 km away from Mexico City, producing the collapse of at least 46 structures in the capital (Alberto et al., 2018; Buendía & Reinoso, 2019). Both events left behind many buildings with medium and severe damages in the central and south region of the country.



USGS Puebla-Morelos MW 7.1 Earthquake Intensity Map Report

	Housing units	
State	Damaged	Total loss
State of Mexico	6,059	2,468
Mexico City	5,765	2,273
Morelos	15,352	1,323
Puebla	27,812	3,214
Oaxaca	63,336	21,823
Chiapas	59,397	18,058
Tlaxcala	34	0
Guerrero	2,976	1,451

Affected housing units per State as result of the Earthquakes of the 7th and 19th September, 2017 (Senado de la Republica, 2017).

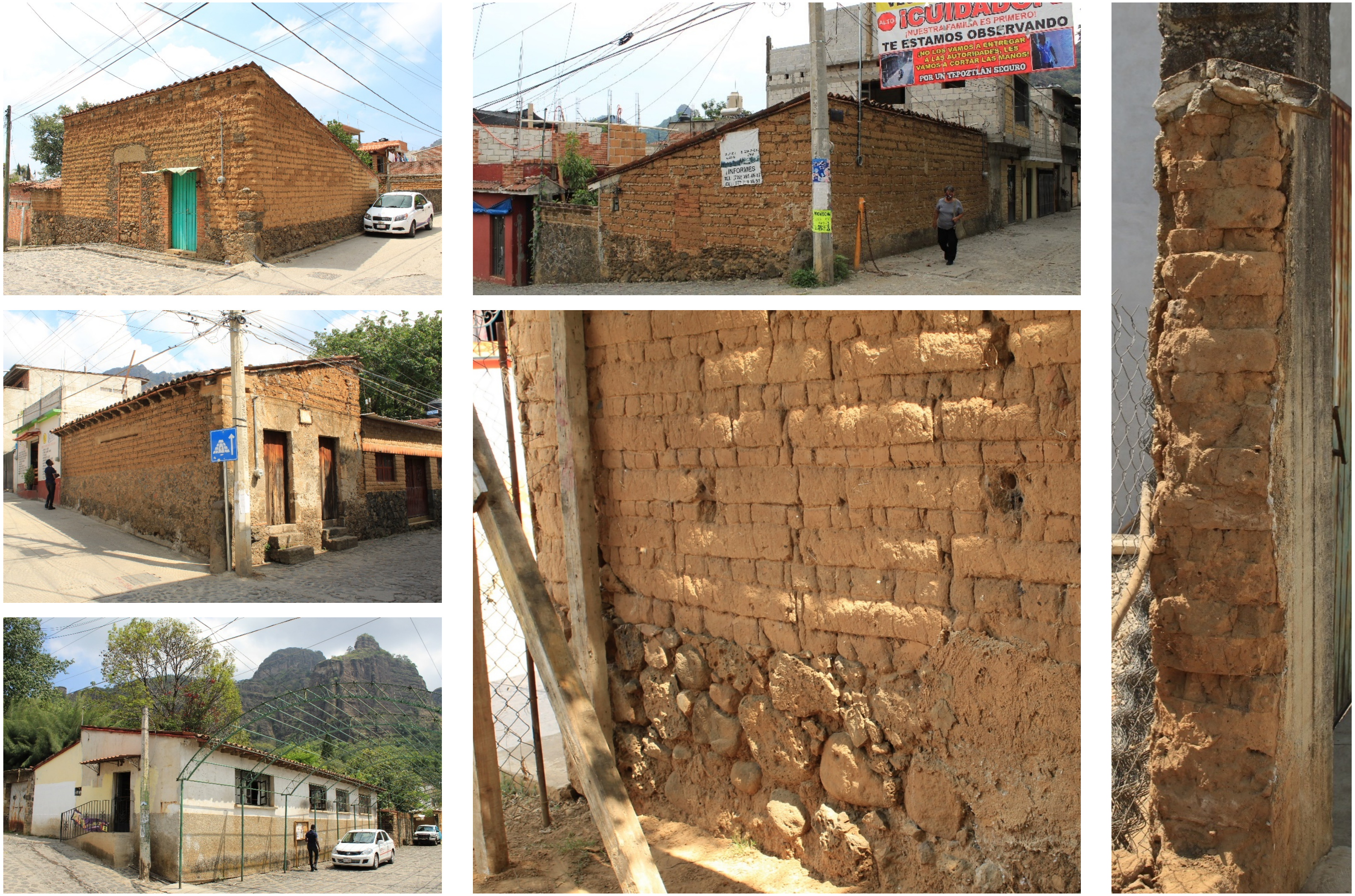
Background: damages in cultural assets and housing

The Mexican Secretary of Culture estimated 2,678 historical monuments affected, including 1,680 temples built before the year 1900 (Lara et al., 2017). The presence of these ancient houses is particularly significative in the states of Morelos, where damages were proportionally more extensive (Galvis et al., 2017). Adobe structures in Morelos represent ca. 5.0% of housing units, reaching proportions of more than 20% in certain municipalities (Sánchez Calvillo et al., 2021).

School in Yautepec

Train station in Jojutla

Background: damages in cultural assets and housing



Typical structures in the rural environments of Morelos

Background: cultural loss and lack of knowledge

There was a systematic replacement of damaged adobe constructions with new houses by using more industrial materials, including prefabricated modules, disregarding reparation and strengthening actions. This was the product, among others, of the lack of reliable techniques for assessing the safety and vulnerability of existing constructions.

This work (January–August 2022) was aimed to propose an objective vulnerability assessment of adobe constructions under the basis of retrospective damage analysis.

The main stages were:

- A parametric approach for seismic intensity / damage analysis. The results were compared with the damages after the 2017 Earthquake.
- A Machine Learning algorithm was trained for perfectioning the approach.
- A series of experimental analyses were carried out in order to characterise the typical mechanical properties of adobe in the municipality of Tepoztlán, Morelos.

Example of new houses for replacing adobe damaged buildings. (Isadora Hastings).

Field characterisation campaign: vulnerability survey

The version of the Vulnerability Index Method (VIM) used on this experimental campaign coincides with the one reported for Atlixco, Puebla (Ramírez Eudave et al., 2022). Each parameter is graduated in four different classes related to seismic behavior of the structure.

Parameters	Class (C_{vi})				Weight (p_i)	Relative weight
BP1. Type of resisting system	0	5	20	50	2.50	16.67
BP2. Quality of the resisting system	0	5	20	50	2.50	16.67
BP3. Conventional strength	0	5	20	50	1.00	6.67
BP4. Maximum distance between walls	0	5	20	50	0.50	3.33
BP5. Number of floors	0	5	20	50	0.50	3.33
BP6. Location and soil conditions	0	5	20	50	0.50	3.33
BP7. Aggregate position and interaction	0	5	20	50	1.50	10.0
BP8. Plan configuration	0	5	20	50	0.50	0.33
BP9. Height regularity	0	5	20	50	0.50	0.33
BP10. Wall façade openings and alignment	0	5	20	50	0.50	0.33
BP11. Horizontal diaphragms	0	5	20	50	0.75	4.91
BP12. Roofing system	0	5	20	50	2.00	13.09
BP13. Fragilities and conservation status	0	5	20	50	1.00	6.86
BP14. Non-structural elements	0	5	20	50	0.75	5.14

Summary of parameters, classes and weights of the parametric vulnerability assessment method as used in (Ramírez Eudave et al., 2022)

Field characterisation campaign: damage grades

A global vulnerability index I_{vf}^{*} is obtained as the weighted sum of all parameters (Eq. 1) and its later normalised for obtaining a vulnerability value V (Eq. 2).

An approach for estimating the level of damage μ_D={0:5} is given in Eq.4. This expression includes the seismic intensity (in MMI scale) and a ductility factor for the structure Q={1:4}.

The damage grade μ_D is framed in the EMS-98 damage scale.

$$I_{vf}^{*} = \sum_{i=1}^{14} C_{vi} \times p_i \quad (1)$$

$$I_v = \frac{I_v^{*} \times 100}{750} \quad (2)$$

$$V = 0.592 + 0.0057 \times I_v \quad (3)$$

$$\mu_D = 2.5 + \left[3 \times tanh\left(\frac{I_{EMS-98} + 6.25 \times V - 12.7}{\mathrm{Q}}\right)\right] \times f(V,I); 0 \leq \mu_D \leq 5 \quad (4)$$

$$f(V,I) = \begin{cases} e^{\frac{V}{(2\times I-7)}} & I \leq 7 \\ 1 & I > 7 \end{cases} \quad (5)$$

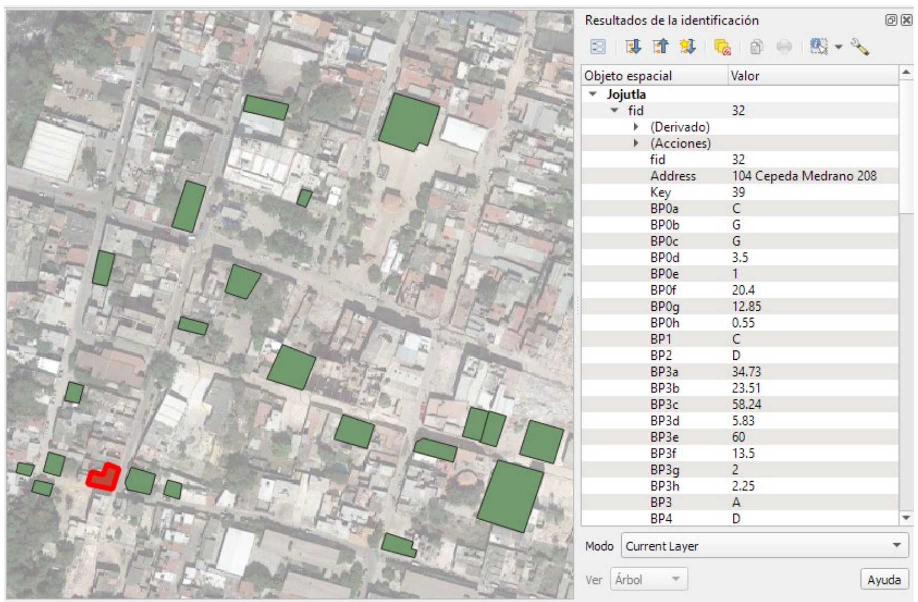
Discrete damage grades, D_k	Range for the mean damage grades μ_D^-	μ_D^+
D_0 – No damage. No observed damage.	0.00	0.50
D_1 – Slight damage. Presence of very localised and hairline cracking.	0.50	1.42
D_2 – Moderate damage. Cracks around openings; localised detachment of wall coverings (plaster, tiles, etc.).	1.42	2.50
D_3 – Severe damage. Opening of large diagonal cracks; significant cracking of parapets; masonry walls may exhibit visible separation from diaphragms; generalised plaster detachment.	2.50	3.50
D_4 – Very severe damage. Façade walls with large areas of openings have suffered extensive cracking. Partial collapse of the façade (shear cracking, disaggregation, etc.).	3.50	4.00
D_5 – Destruction. Total in-plane or out-of-plane failure of the façade wall.	4.00	5.00

Discrete qualitative levels of damage and corresponding intervals according to the EMS-98 approach

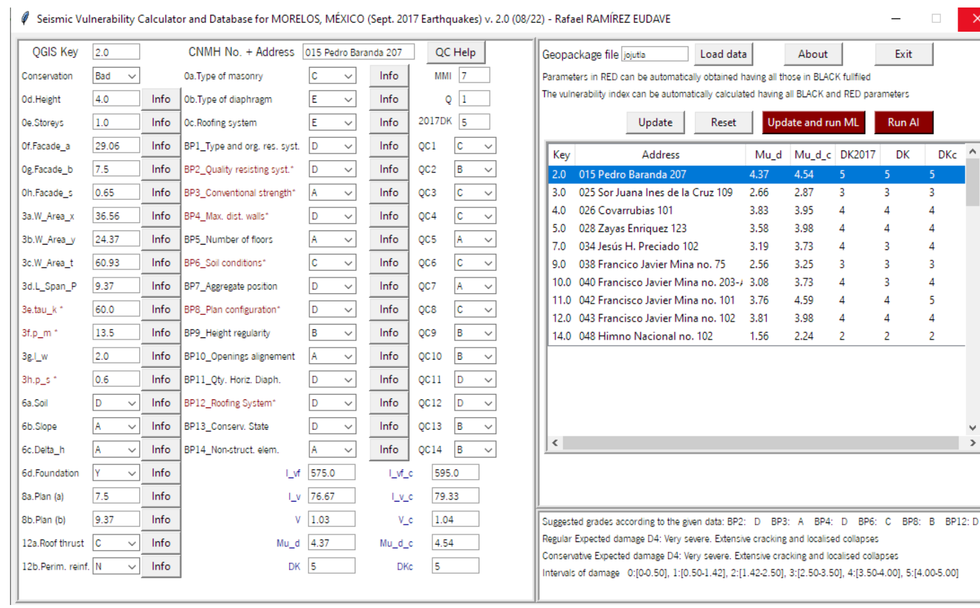
Field characterisation campaign: GIS database

A Geographic Information System in the QGIS (version 3.12 București) environment was used for storing and managing the data of this study. This permitted the access and edition of the database from mobile devices (Ramirez Eudave et al., 2022).

A Python-based front-end was programmed for performing reading and edition actions on the database, facilitating data management and calculations while keeping the integrity of the database.



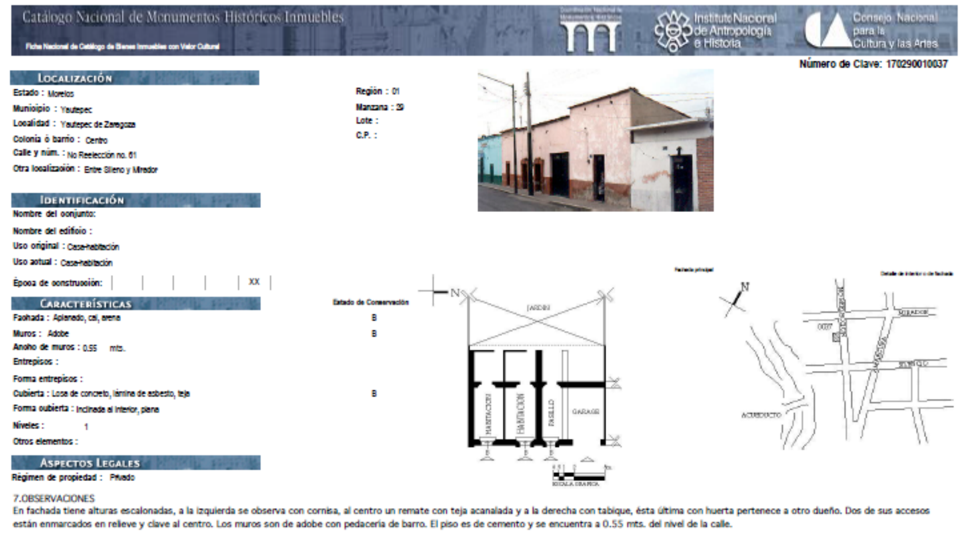
Screenshot of the GIS database in QGIS



Screenshot of the Python-based GUI interface

Field characterisation campaign: data acquisition

- Visual confirmation of the descriptive information contained in the National Catalogue of Historical Monuments.
- Photographical survey. In many cases, the access was restricted.
- Damage questionnaire. The people were asked to describe the damages experienced after the 2017 Earthquakes. The diagram of the EMS-98 damage scale was shown in order to better classify the level of damage.
- Obtention of general dimensions (e.g., exterior measures for contextualizing the architectonic plan drawing of the Catalogue).
- Acquisition and grading of missing parameters.


Catálogo Nacional de Monumentos Históricos Inmuebles
Ficha Nacional de Catálogo de Bienes Inmuebles con Valor Cultural
Instituto Nacional de Antropología e Historia
Consejo Nacional para la Cultura y las Artes
Número de Clave: 170290010037

LOCALIZACIÓN
Estado : Morelos
Municipio : Yautepec
Localidad : Yautepec de Zaragoza
Colonia ó barrio : Centro
Calle y núm. : No Reelección no. 61
Otra localización : Entre Sileno y Mirador

Región : 01
Manzana : 29
Lote :
C.P. :

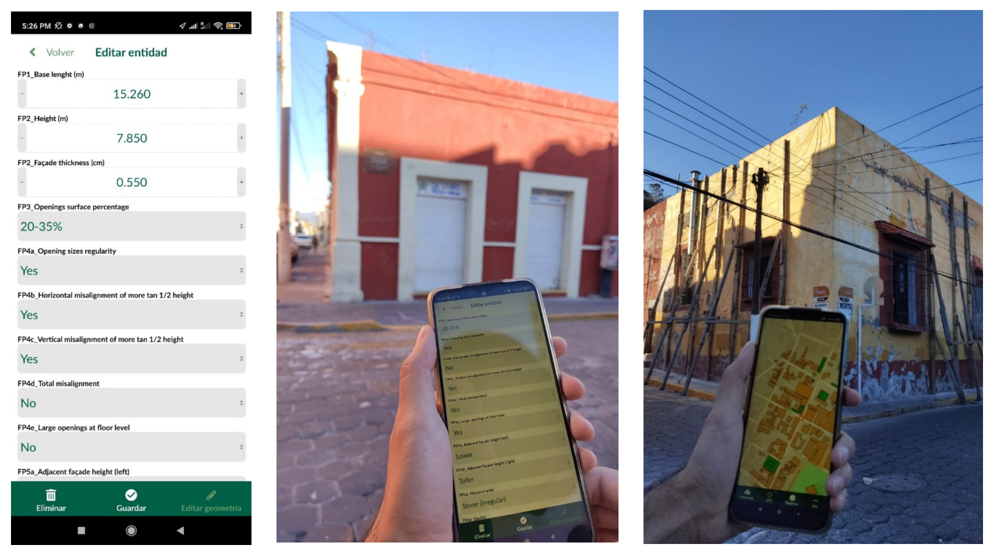
IDENTIFICACIÓN
Nombre del conjunto:
Nombre del edificio :
Uso original : Casa-habitación
Uso actual : Casa-habitación
Época de construcción: | | | | | XX |

CARACTERÍSTICAS (Estado de Conservación)
Fachada : Aplanado, cal, arena — B
Muros : Adobe — B
Ancho de muros : 0.55 mts.
Entrepisos :
Forma entrepisos :
Cubierta : Losa de concreto, lámina de asbesto, teja — B
Forma cubierta : Inclinada al interior, plana
Niveles : 1
Otros elementos :

ASPECTOS LEGALES
Régimen de propiedad : Privado

7.OBSERVACIONES
En fachada tiene alturas escalonadas, a la izquierda se observa con cornisa, al centro un remate con teja acanalada y a la derecha con tabique, ésta última con huerta pertenece a otro dueño. Dos de sus accesos están enmarcados en relieve y clave al centro. Los muros son de adobe con pedacería de barro. El piso es de cemento y se encuentra a 0.55 mts. del nivel de la calle.

National Catalogue of Historical Monuments entry

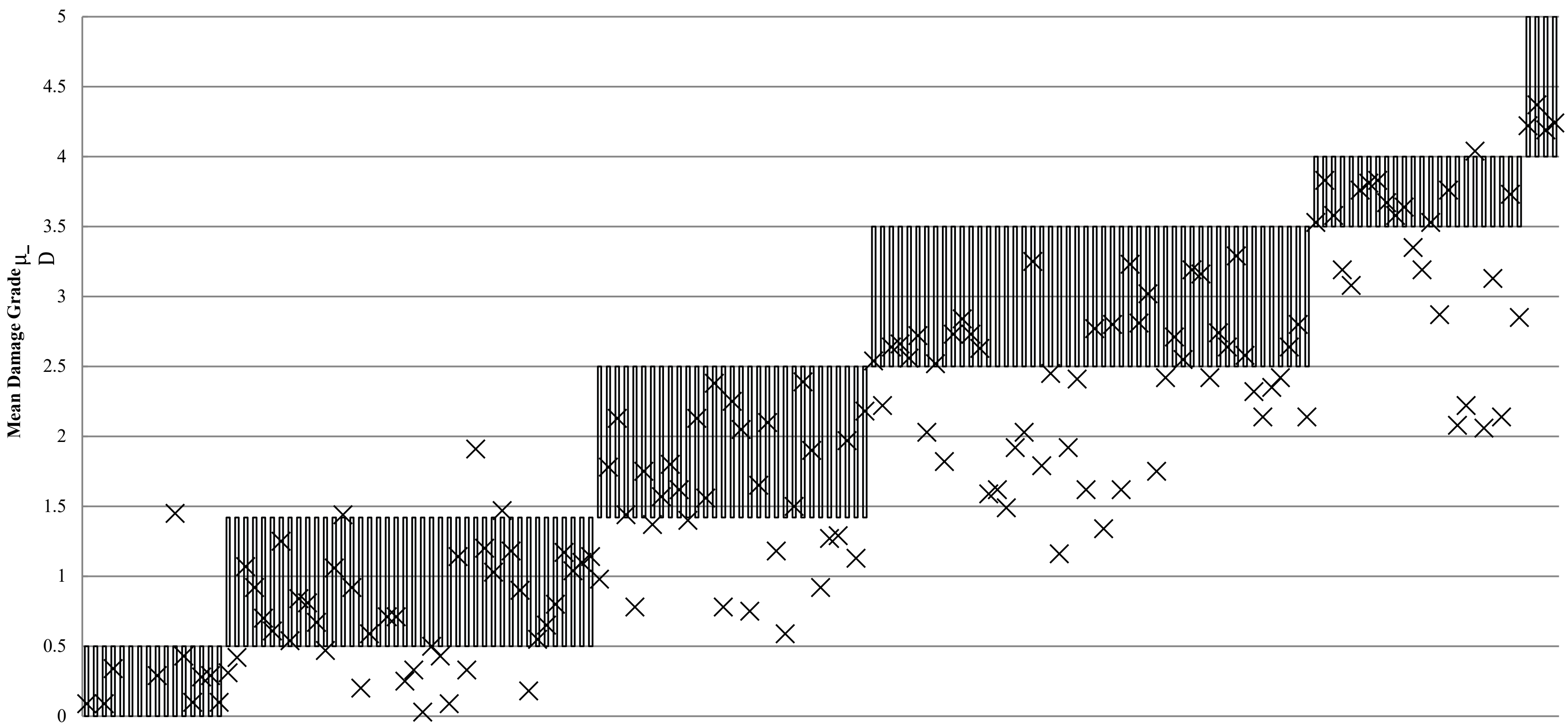


Example of remote edition of the GIS database from the site

Field characterisation campaign: data analysis

In total, 167 buildings were assessed. The first comparison consisted in checking if the analytical value obtained for μ_D was comprised in the interval of the real damage $D_{k,2017}$.

A total of 104 out of the 166 samples (62.28%) accomplished this initial condition

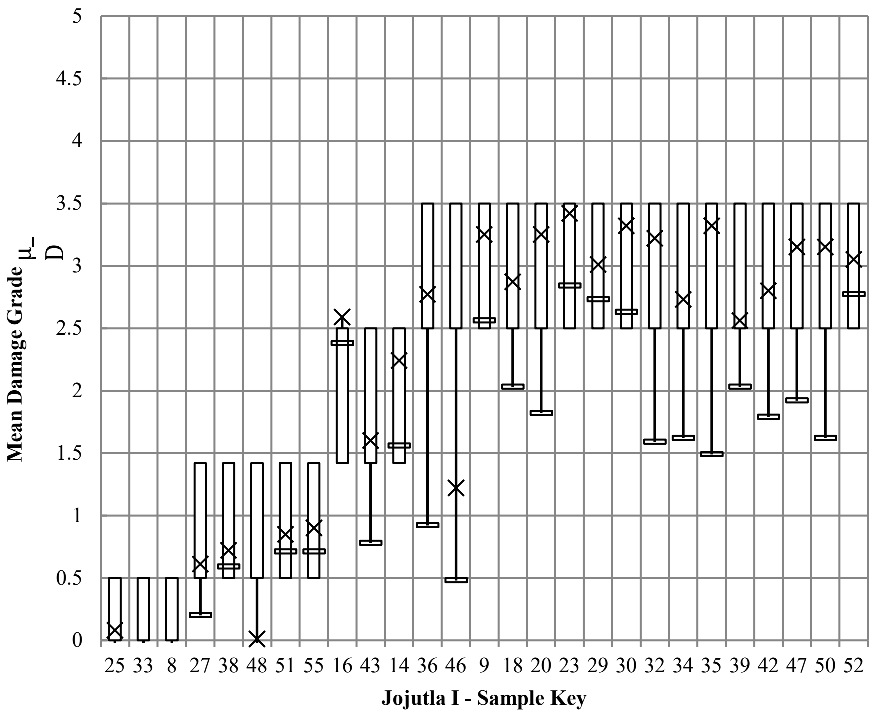


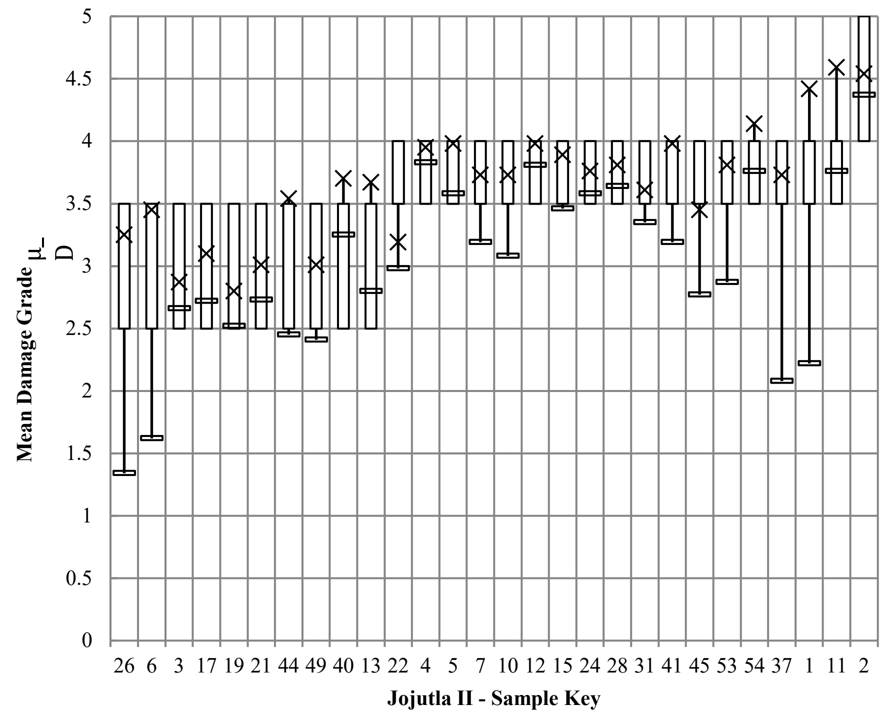
Comparative between the intervals for real damage (bars) and analytical damage (black crosses)

Field characterisation campaign: data analysis

Given the limitations during the field works it was decided to consider the interval-based approach proposed for the city of Atlixco (Ramírez Eudave et al., 2022). This approach offers an analytical damage interval μ_D and $\mu_{D,conservative}$, facilitating the interpretation of the overlapping among both intervals.

With this approach, the vast majority of predicted damage intervals (93.41%) are been overlapped with the corresponding intervals of observed damages



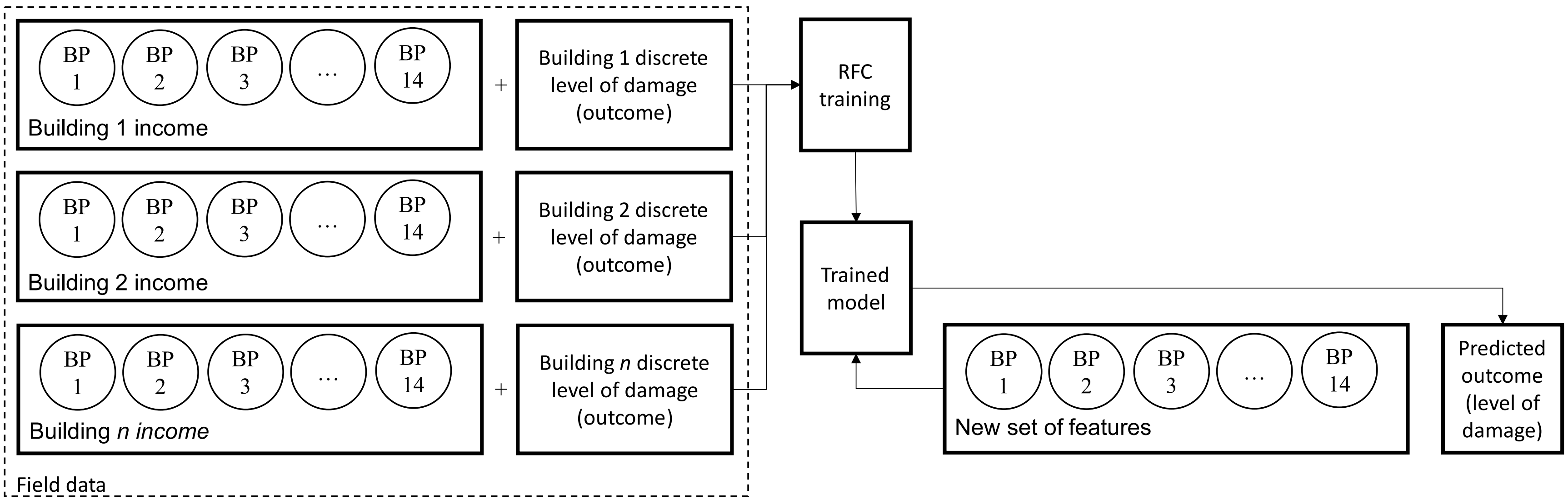


Comparative between the intervals for real damage (bars), analytical damage (black bar) and conservative analytical damage (black crosses)

Field characterisation campaign: Machine Learning

Given that the proposed procedure is intrinsically attached to a regressive analysis on cause-effect categorised elements (both for the parameters and the damages), the use of computational analysis may be strongly suitable for expanding the boundaries of this methodology.

For this work, a Supervised Learning approach (i.e., data for training the association between features and specific outcomes that we expect to further predict for new sets of features) was conducted.

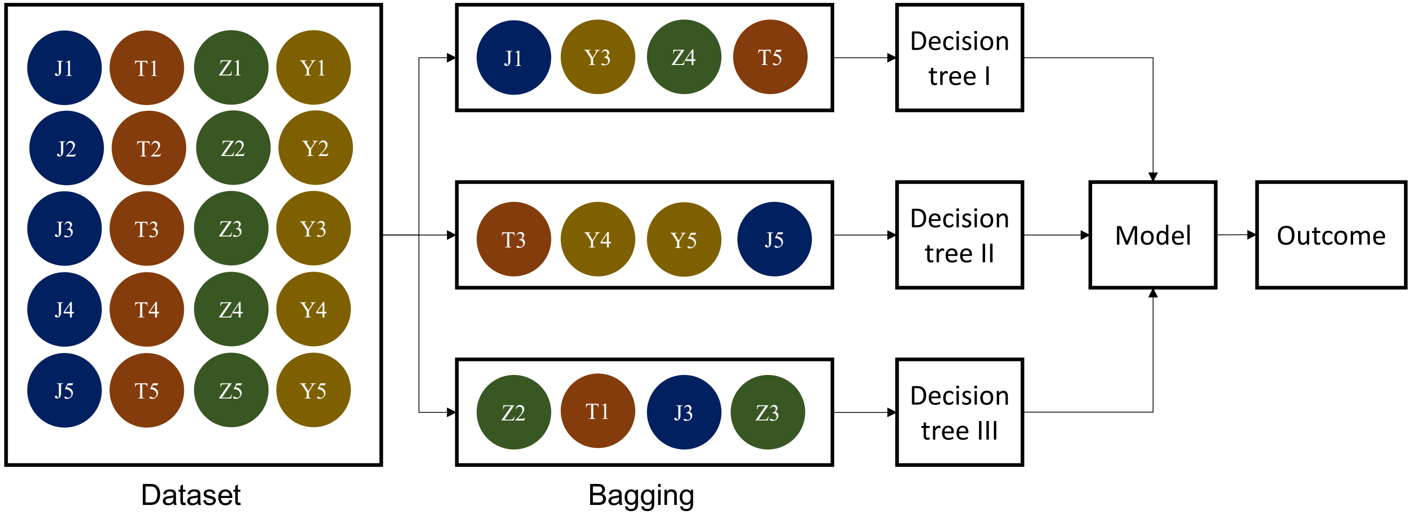


Schematisation of the training procedure of the model

Field characterisation campaign: Machine Learning

By following the observations of (Buitinck et al., 2013), this problem was modelled by the means of the Random Forest Classifier (RFC) learning algorithm, that ensembles numerous decision trees (i.e., flowchart models in which an outcome is product of a specific path of several conditional statements or nodes) that fit fractions of data instead of creating a unique tree model.

Data is split in several random subsets that will train different independent models. For this process, a random selection of 80% of field data was used for training the model, while the other 20% was later used for assessing the accuracy of the model.



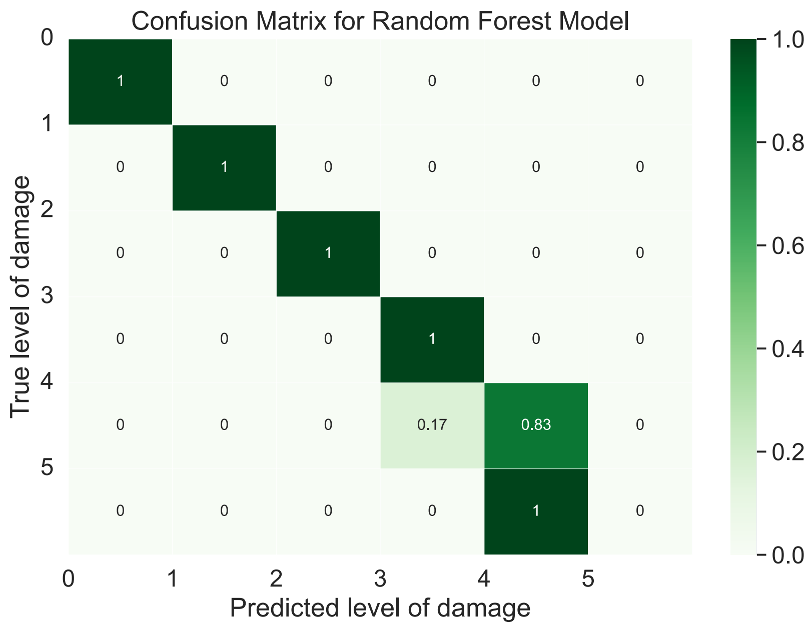
Schematisation of the bagging and decision tree assembling processes.

Field characterisation campaign: Machine Learning

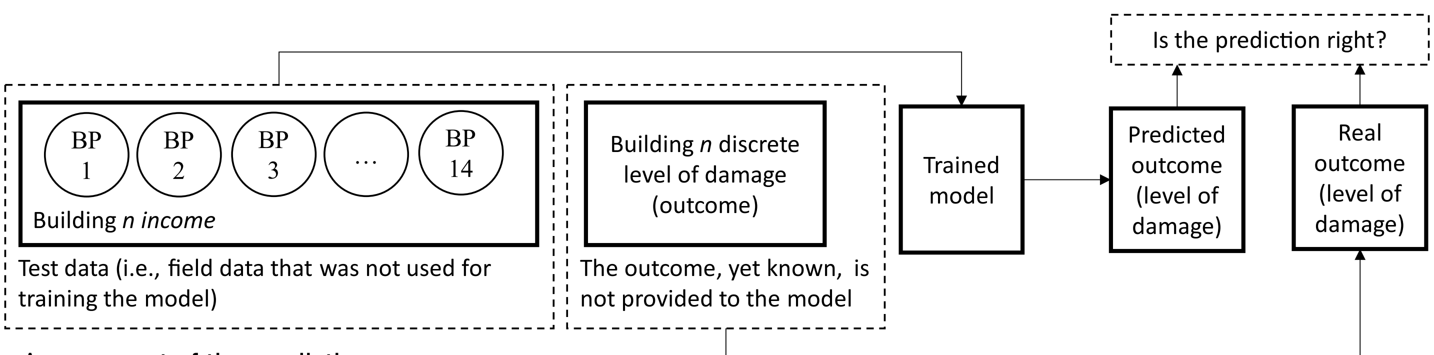
A series of predicted classifications were obtained by using the income data reserved for testing the model (34 random samples).

The correspondence between the true and predicted damage grades is shown in the confusion matrix. It exhibits how most of the classes were correctly identified by the model, but there is a lack of representativeness for identifying the level of damage $D_K = 5$.

This phenomenon can be easily associated to the relatively small number of samples that presented this class (4 out of 167, 2.4%, but it appears only once in the test split of the sample).



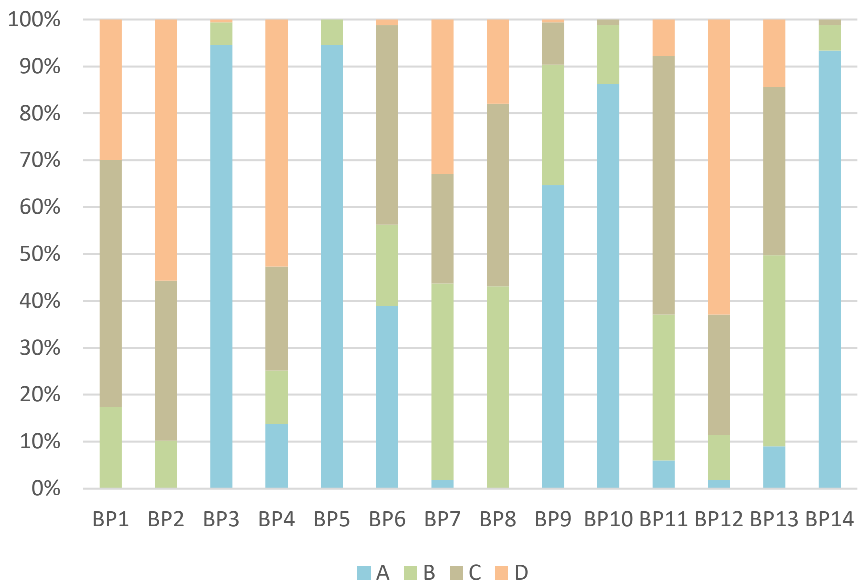
Confusion Matrix



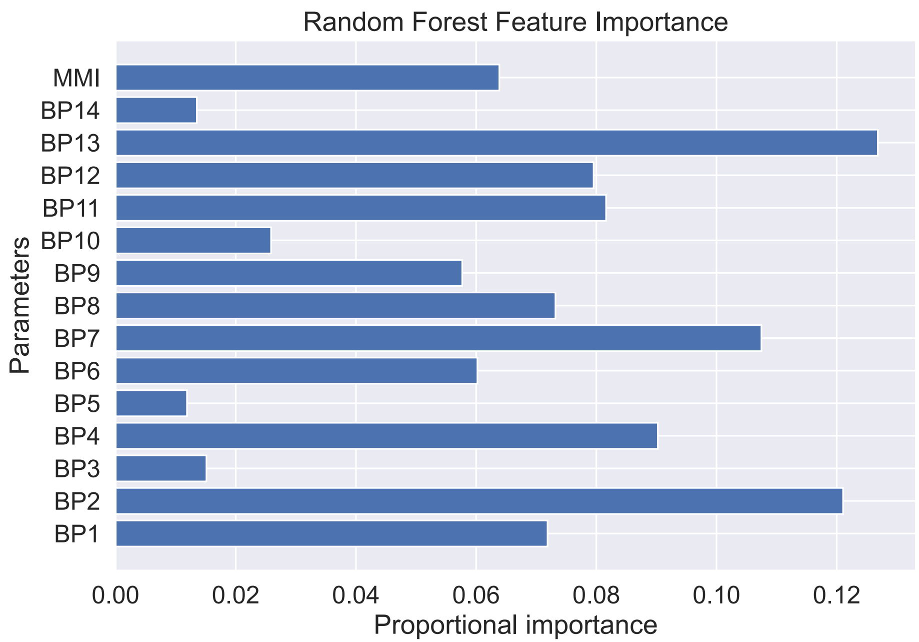
Assessment of the prediction accuracy

Field characterisation campaign: Machine Learning

It is possible to retrieve which is the relative impact that every parameter has for the classification process. At this point, it becomes convenient to be aware of the limits imposed due to the variability throughout the sample, i.e., the impact of a determined parameter will be smaller if it does not present relevant variations for differencing samples. The sample studied in this work presented a relatively small variation of some parameters given the typological coherence among the structures.



Parameter grade distribution throughout the whole sample



Proportional importance by parameter according to the ML model

Current works (Jan – Aug 2022, México)

Current works: experimental test analysis

In parallel to the data acquisition and analysis herein performed, a series of tests were in Tepoztlán for determining the velocity of propagation for ultrasonic waves.

A total of 39 tests in 13 different buildings were performed. The results are still under analysis.

Ultrasonic testing campaign

Current works: experimental test analysis

A set of adobe pieces from a historical construction (recovered from partially collapsed walls) was donated for performing laboratorial experiments. The experiments were aimed to find the compressive strength, modulus of elasticity and Poisson ratio for the typical building material found in the studied region.

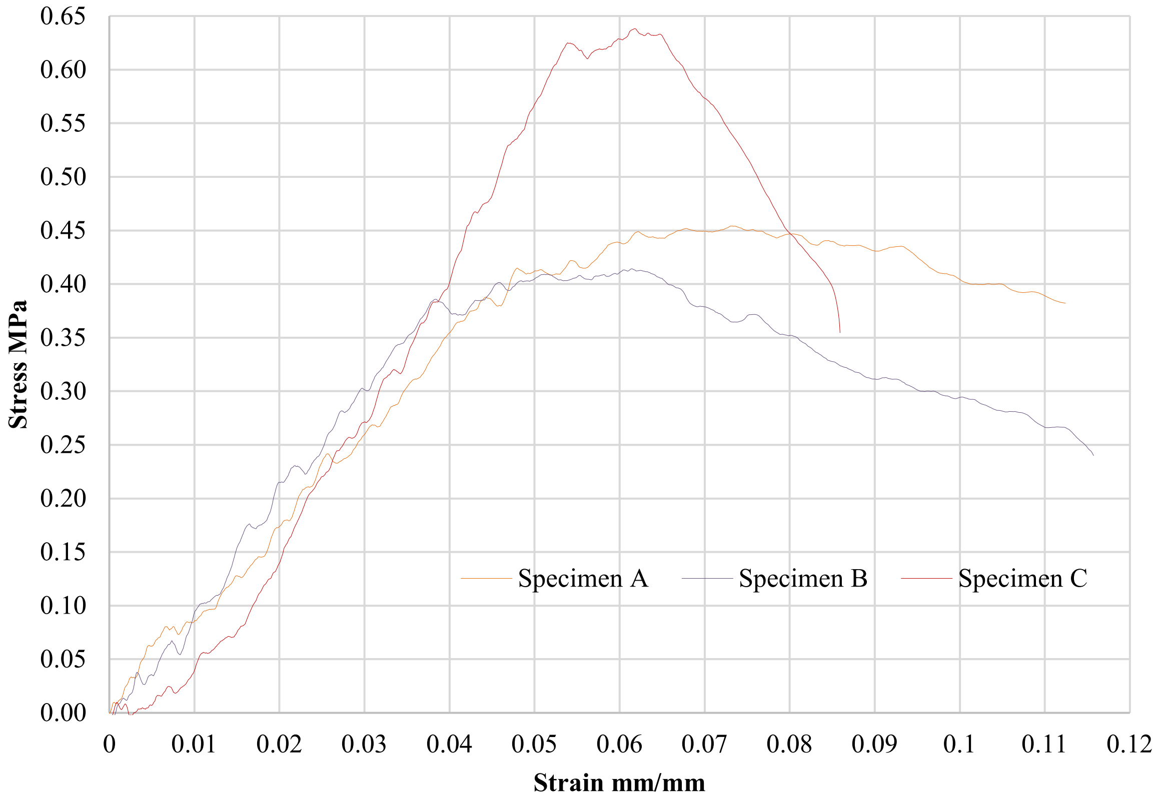
All the tests were performed in the Structures Laboratory of the Institute of Engineering of the National Autonomous University of Mexico, by using a universal testing machine.

Set of adobes in situ and prepared for testing

Current works: experimental test analysis

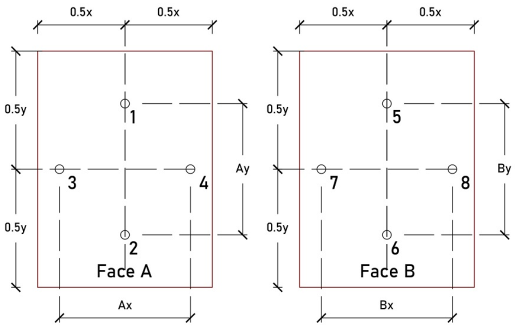
a) Preliminary compressive tests until the failure of the small samples (A, B, and C) for obtaining an estimate of the compressive strength for the material. This value can then be used to calibrate suitable load cycles for the remaining samples;

First tested sample

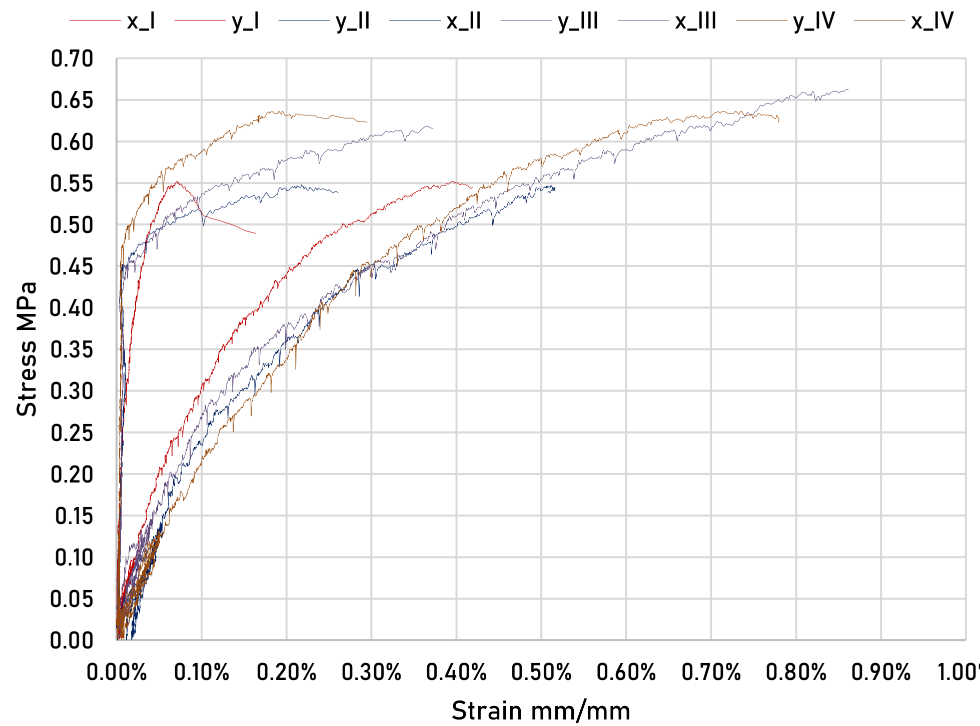


Current works: experimental test analysis

b) Compressive tests on the complete adobe blocks (I, II, III and IV) with three cycles of charge and discharge below the indicative elastic limits of compressive strength. Strains were monitored by the means of an OptoTrack system.



Setup of the OptoTrack system



Final remarks

- The assessment of **the seismic vulnerability of historical constructions is fundamental for mitigating cultural losses** after a seismic event.
- **The presented approach has been demonstrated to be suitable**, despite some limitations identified during the field data acquisition campaigns.
- **The use of trained machine learning algorithms seems to be suitable** for taking advantage of the parametric vulnerability survey in order **to provide more realistic predictions** when applied to a typological context.
- **It is possible to easily include new evidence by using trained algorithms**. Nevertheless, it is always necessary to support the observations with complementary evidence.
- Despite the results of the NDT and laboratory tests are still preliminary, **there seems to be some homogeneity across the analysed constructions** in Tepoztlán, which may support the extrapolation of the conclusions reached from the compressive tests of adobe.

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Thank you