International Journal of Disaster Risk Reduction 74 (2022) 102909

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Parameter-based seismic vulnerability assessment of Mexican historical buildings: Insights, suitability, and uncertainty treatment

Rafael Ramírez Eudave [a,*], Tiago Miguel Ferreira [b], Romeu Vicente [c]

[a] University of Minho, ISISE, Department of Civil Engineering, Guimarães, Portugal, 4800-058, Guimarães, Portugal
[b] University of the West of England, Department of Geography and Environmental Management, Bristol, BS16 1QY, UK
[c] RISCO, Department of Civil Engineering, University of Aveiro, Aveiro, Portugal

ARTICLE INFO

Keywords:
Seismic vulnerability
Historical monuments
Vulnerability assessment
Index-based methods
Historical centres
Puebla 2017 earthquake
Atlixco
Puebla

ABSTRACT

The seismic vulnerability assessment of large sets of constructions is meaningful for anticipating post-earthquake scenarios in the context of loss prevention and resilience. These activities must overcome several difficulties related to the size and heterogeneity of the building stock, becoming even more complex when addressed to historical and vernacular structures. The analysis of post-earthquake data has permitted the design of vulnerability assessment methods based on the identification of parameters related to the geometrical, structural and material features that rule the seismic behaviour of different typologies. A dataset of information about the 2017 Earthquakes in Mexico is used to discuss the suitability of a pre-established seismic vulnerability index approach. The compatibility between this approach and the information contained in the National Catalogue of Historical Monuments is the departure point for estimating levels of damage, which are then compared with those recorded in 2017. This implementation requires a series of adaptations and strategies, including the adjustment of the description of the parameters for the Mexican context and the development of a strategy for considering the uncertainty when the information is limited, offering an alternative more conservative output. Based on the results of the comparison between the levels of damage estimated using the vulnerability index approach adopted in this paper and those recorded in the aftermath of the 2017 Earthquakes in Mexico, it is plausible to confirm that this approach can be used in future seismic vulnerability assessment works in this region, provided that the limitations identified and discussed here are considered.

1. Introduction

The report on Economic Losses, Poverty and Disasters from 1998 to 2007 [1] contextualises how earthquakes are the natural events with the highest ratio of deaths by occurrence worldwide. While earthquakes represent only 7.8% of natural disasters on the planet between 1998 and 2017, they are related to 56% of casualties related to natural events. Among the major categories of disasters, earthquake is the one that threatens human lives the most. It is relevant to recognise that most casualties and losses are related to a relatively small number of events with a high magnitude.

The Global Assessment Report on Disaster Risk Reduction Atlas [2] presents a so-called Annual Average Loss, an average amount

* Corresponding author.
E-mail addresses: r.92@outlook.es (R. Ramírez Eudave), Tiago.Ferreira@uwe.ac.uk (T.M. Ferreira).

https://doi.org/10.1016/j.ijdrr.2022.102909
Received 5 November 2021; Received in revised form 27 February 2022; Accepted 11 March 2022
Available online 26 March 2022
2212-4209/

that each country could expect to lose every year due to natural events. This report estimates that Mexico has a range between 1001 and 2000 million USD of annual losses due to earthquakes, resulting from an unfortunate combination of a high rate of occurrence (namely related to a relevant source of seismic activity on the south coast of the country) and a significant socioeconomic vulnerability. Mexican building stock has also been shown highly vulnerable to moderate to high magnitude seismic events. Authors such as Caprano et al. [3], for example, have estimated reparations costs between 2000 and 4500 million USD for the seismic events of 2017 only.

The damages of the 2017 earthquakes are reflected in almost 180,000 affected housing units, approximately 0.56% of the national housing building stock. This proportion, however, is much more significant when focused on the most affected states, such as Oaxaca (6.07%), Chiapas (4.71%) and Puebla (1.79%), which also present high grades of marginalisation. Some municipalities reached records of more than 40% of housing units affected by the seismic events. These states also concentrate a relevant proportion of housing units corresponding to vernacular and/or historical constructions. For example, the National Catalogue of Historical Monuments [4] mentions 2804 historical monuments (i.e., constructions built before the year 1900) that are currently used as a house in the state of Oaxaca. Ancient housing units also represent more than half of historical monuments in Puebla and Chiapas' states (Table 1). This phenomenon corresponds to a pattern in which the built environment is still rich in vernacular expressions and traditional construction techniques, especially in historical cities. It is relevant to point out that the investment for attending non-residential historical monuments (namely churches) would exceed 600 million USD [5], concentrated in states with a high level of marginalisation. In fact, more than 50% of the historical buildings damaged by the 2017 Earthquakes are located in the states of Puebla and Oaxaca [6].

Therefore, a large-scale assessment of the seismic vulnerability of constructions would permit adopting proactive actions to limit losses due to seismic events. Even if there is vast knowledge about seismic occurrences in the country, there is still a gap related to the large-scale seismic vulnerability assessment of buildings. More specifically, the protection of cultural heritage depends on the proactive identification of the vulnerable constructions for carrying strategic interventions, sometimes based on maintenance or minor actions.

This article will discuss and identify the components of seismic risk to highlight the relevance of performing large-scale seismic vulnerability assessment exercises towards the outline of effective risk mitigation strategies. It will be discussed how to analyse the seismic vulnerability of historical and/or vernacular constructions, specifically adobe and masonry structures (which are predominant in most of the country's regions). An existing methodology based on parameters will be presented. The inputs, processes and outputs will be discussed to assess the suitability of the method in the context of the Mexican typologies. An application of the method in buildings of the historical city of Atlixco, Puebla, will permit insight into the limitations and challenges of applying the methodology, given the availability of data for large sets of constructions. The comparison between the preliminary results of the method against the real damages observed after the Puebla 2017 earthquake will permit to feed a discussion about the sources of uncertainty, some potential strategies for dealing with it and a potential typological adaptation. These results will also be meaningful for carrying sensitivity analysis aimed at outlining some general axis for adapting the methodology to the Mexican context, allowing a potential large-scale assessment tool for Mexican historical centres.

2. Seismic risk assessment

A vast number of concepts are empirically related to risk, namely because it is intrinsically associated with any activity or system. Sometimes this semantical divergence leads to misuses or confusions that difficult to characterise risk in certain contexts appropriately.

2.1. *Definition of risk*

A very generalised and wide description of risk may be found in the international standard ISO 31000, related to the principles and guidelines for risk management [7]). This document states that « risk» is the uncertainty of achieving objectives due to external factors and influences. Risks are able to be identified, analysed and assessed, permitting further treatment until they become acceptable. The management of risks is a necessary step for increasing the likelihood of achieving objectives, having an awareness of threatening sources. Furthermore, it has a key role in improving governance, establishing a basis for decision-making and planning to minimise losses. Even though the ISO 31000 introduces all these concepts in the context of «organisations», all of them apply to individuals and material assets as well. The definition of risk unfolds a series of aspects that can be understood as the «objectives » for risk analysis purposes, such as financial, health, safety or environmental goals. Risk is characterised by referring to the potential events and consequences, combining the potential consequences with the likelihood of occurrence of the events. When addressed for seismic events, they can be contextualised according to the standard, as shown in Table 2, in which the concepts found in the ISO 31000 standard are applied to the effects that a seismic event of a determined magnitude would have in historical constructions.

In the context of the ISO 31000 standard, the evaluation of the seismic risk of historical constructions can be based on the uncertainty of sustaining the performance conditions of a building (structural safety and/or functions) when it is subjected to dynamic loads. It is worth mentioning that the occurrence of a seismic event of a determined intensity, the level of damage, and the economic and human losses can all be represented by probabilistic functions. However, in this work, the goal is to get fragility curves that

Table 1
Number of historical monuments and housing units that are considered historical monuments in the states of Oaxaca, Chiapas and Puebla, according to Ref. [4].

State	Historical monuments	Houses considered historical monuments
Oaxaca	5587	2804
Chiapas	2304	1514
Puebla	11359	6463

Table 2
Concepts as defined in the ISO 31000 and contextualised for assessing the risk of an earthquake of a determinate magnitude.

Concept	Definition according to ISO 31000	Application in the context of seismic risk for historical constructions
Risk	Effect of uncertainty on objectives	Uncertainty on sustaining the structural performance of constructions (objective), i.e., damage or failure of the structures
Risk evaluation	Process of comparing the results of the risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable	Comparison of the expected damages for a determined seismic magnitude to assessing how tolerable is
Risk criteria	Terms of reference against which the significance of a risk is evaluated	The threshold for determining the acceptability of structural damage and/or loss of functions on the constructions
Risk source	Element which alone or in combination has the intrinsic potential to give rise to the risk	Geological, volcanic or other sources of earthquakes
Event	Occurrence or change of a particular set of circumstances	Dynamic excitation of the structures as a result of a seismic event
Consequence	The outcome of an event affecting objectives	Post-event scenario in terms of damages (fragility curve)
Likelihood	Chance of something happening	Function of return periods for a determined seismic intensity

correlate the probability of different damage states being reached or exceeded for certain seismic intensities. Therefore, given the vulnerability level of the constructions, a probabilistic function for a seismic event (i.e., characterised by its intensity) would describe an approximated level of damage and loss, facilitating the adoption of risk criteria.

According to the Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas [8] of the Mexican National Centre for Prevention of Disasters (CENAPRED), disasters are the consequence of the presence of a risk condition, related to a perturbation over an exposed asset. Furthermore, the risk associated with disasters involves the probability of loss and depends on the vulnerability and threats. Therefore, CENAPRED encourages the development of the characterisation and quantification of the threats and the grade of vulnerability as a primary action for effectively mitigating the effects of threatening events. This guide generically considers the vulnerability as a function involving the intensity of the phenomenon (such as the intensity or the spectral acceleration when addressed to earthquakes) and the probability of damage and/or loss in a determined asset, including the extended impact that it may have. This damage estimative depends on the system and can be quantified based on several indicators, such as social or economic. However, any vulnerability analysis must classify and determine the exposed systems (i.e., must be based on a characterisation), establish thresholds for assessing the damages or losses, and, finally, express the potential scenarios for the exposed assets.

Despite the popularity of the classical definition of risk as a measure of the probability and severity of adverse effects or the triad Risk $=$ Threat $\otimes$ Vulnerability $\otimes$ Consequence, Haimes [9] identify risk as a vector with the units of the consequences. It is given as a function of time, the probability of the threat (initiating event), the probability of the consequences (given the threat), the state of the system (e.g., its vulnerability) and the resulting consequences. For example, in the context of seismic risk, the risk would be able to be understood as a vector in the units of damage or losses.

Risk definition always needs the identification of the vulnerability of the systems and elements exposed to a given threat. Since no successful risk evaluation, mitigation or control can be carried out without the analysis and characterisation of the vulnerability, suitable approaches for framing the specific vulnerability of elements towards the studied phenomena must be designed and put in place. Just as for risk, the concept of vulnerability needs to be clearly defined in order to contextualise it in a determined analysis.

2.2. Definition of vulnerability

The concept of vulnerability has a broad utilisation throughout multiple and variate disciplines, namely to refer to a certain capacity for coping with change. The conceptual analysis of Brooks [10] express that, in general, vulnerability is measured through outcome indicators, i.e., expectable losses and/or damages. This analysis also gathers some definitions of vulnerability, emphasizing that of the International Panel on Climate Change: «The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and adaptive capacity».

In the same line, De Luca [11] defines seismic vulnerability as « … the degree of loss to a given element at risk (e.g., buildings) resulting from the occurrence of an earthquake event». The definition offered by Gavarini [12] is even more specific since it is framed on the structural performance of constructions in historical centres: « … the seismic vulnerability of a building is a quantity associated with its 'weakness' in front of earthquakes of a given intensity so that the value of this quantity and the knowledge of seismic hazard allow to evaluate the expected damages from future earthquakes». This causal relation is highlighted by Vicente et al. [13]: «Seismic vulnerability is an intrinsic property of the building structure, a characteristic of its own behaviour to seismic action described by a cause-effect relationship, in which the earthquake is the cause, and the effect is the damage suffered».

The key aspects for contextualising the seismic vulnerability of an element or system are then related to the measurement of an outcome (e.g., level of damage and/or loss) because of its ability to cope with a seismic event. Following this vulnerability approach, it is possible to identify the weakness of those elements for a specific seismic event. It is convenient to recognise that this definition can be extrapolated to historical centres (or, more generically, urban contexts) as systems composed by singular constructions, given the fact that, by definition, any structure has a specific grade of inability to cope with a certain dynamic (seismic) demand.

2.3. Vulnerability in the context of urban scale: challenges and previous experiences

The measurement of the ability of the structures to cope with the demands imposed by earthquakes has to overcome, however, numerous challenges, such as the existence of great volumes of constructions on historical centres, the variety and complexity of structures (namely remarkable dissimilarities in materials and geometry), and the relations that exist between the constructions. In the most favourable but rare cases, common characteristics in a buildings sample are limited to a certain set of materials and relatively homogeneous structural systems [14]. According to Cocco et al. [15], a feasible approach is to analyse large stocks of buildings in order to include the structural parameters that characterise the response of the buildings and involve the parameters' variability. This approach is limited by the effort required to comprehensively investigate and model a large number of samples, which encourages the use of simplified procedures.

The universe of historical buildings is hardly generalisable by any common characteristic (excepting, maybe, the antiquity), but there is a series of major groups that permit to group relevant sets of constructions in determined contexts. When analysing sets of historical buildings in the context of urban centres, it is possible to find some typological similarities that frame most constructions with a certain grade of variability, such as repetitive patterns for structural systems, geometric constants, etc. It is expectable to find a certain typological consistency in historical centres since architecture is namely a consequence of the local availability of resources (workforce, materials, technology), environmental conditions and cultural determinants.

For the above-exposed reasons, the typological approach is very helpful for taking advantage of the similarities among a certain set of constructions (e.g., by analysing similarities that also determine the structural response towards an earthquake) while the typological deviations of each sample permit to individualise and characterise it. In other words, typological approaches permit framing

Table 3
Key concepts according to the Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas.

Concept	Definition according to CENAPRED
Vulnerability	It is a function that involves the intensity of the phenomenon and the expected consequences on a determined asset.
Consequences	Damages and/or losses. It can express the wide impact that the damage or loss would have according to the interruption of functions that the asset represents, e.g., a hospital.
Failure modes	Total failure (collapse) of structure and/or foundations; damages on structural elements (walls and diaphragms); damages on non-structural elements (windows, finishing materials); damages on equipment and mobile assets.

some determinants in the context of the seismic performance of constructions by maintaining the individual-scale analysis of the buildings. Even if the characterisation's uncertainty is still a challenge when performing typological analysis, an adequate definition of the fields to be characterised permits controlling and contextualising the uncertainty. Some sources of typological variety are listed by Ref. [16] and include: type of masonry (e.g., regular brick or rubble stone), characterization of the properties of the materials (units and mortar, masonry as composite), knowledge of their mutual aggregation (in both thickness and façade), and the efficiency of connections among structural components (walls, floors, roof). Most of these characteristics can be parametrised (i.e., to be described based on parameters such as intervals or thresholds) and classified. Furthermore, it is possible to identify sets of characteristics that are determinant for explaining or conditioning the performance or behaviour of a building in fields such as habitability, energetical efficiency or, for instance, seismic behaviour.

Parameter-based seismic vulnerability methods have been widely used worldwide, particularly in countries and regions where seismic activity is more significant or recurring, such as Italy, Greece or Nepal. The Gorkha earthquake (2015), one of the most destructive earthquakes of the recent past, is an outstanding example of a seismic event that has been intensively studied to consolidate and create new knowledge on the seismic vulnerability of various buildings typologies; often resorting to parameter-based vulnerability assessment methods. For example, Gautam et al. [17] analysed more than 3000 schools by defining a series of structural and material parameters that were subsequently scored to obtain vulnerability classes. This work shows the suitability of typological classifications for designing robust descriptions beyond some typical taxonomical descriptions purely based on materials.

3. Seismic vulnerability assessment based on parameters for the Mexican context

The identification and parametrisation of meaningful typological similarities among constructions are indeed based on many of the simplified approaches and methodologies that have been proposed over recent years to assess the seismic vulnerability of existing structures. Some simplified parameter-based methods have presented models for establishing vulnerability functions among specific typologies of constructions, such as the proposal of the National Centre for Prevention of Disasters (CENAPRED) and the so-called Vulnerability Index Method.

3.1. Qualitative assessment of the vulnerability of housing units towards seismic actions (CENAPRED)

The Basic Guide for the Elaboration of Statal and Municipal Threats and Risk Atlas [8] offers a strategy for assessing the seismic vulnerability of housing units. However, this method is based on five levels of seismic vulnerability only, which constitutes a clear limitation – making it hardly useable as a tool to identify and prioritise intervention needs, for example. In Chapter 1.4, «Simplified criteria for qualitatively assessing the vulnerability of housing units towards seismic actions», this document includes a simplified methodology based on a set of concepts related to the materiality of the constructions, the grade of social vulnerability, and the macroseismic region in which a determined municipality is located Values. The criteria behind these concepts are summarised in Table 4.

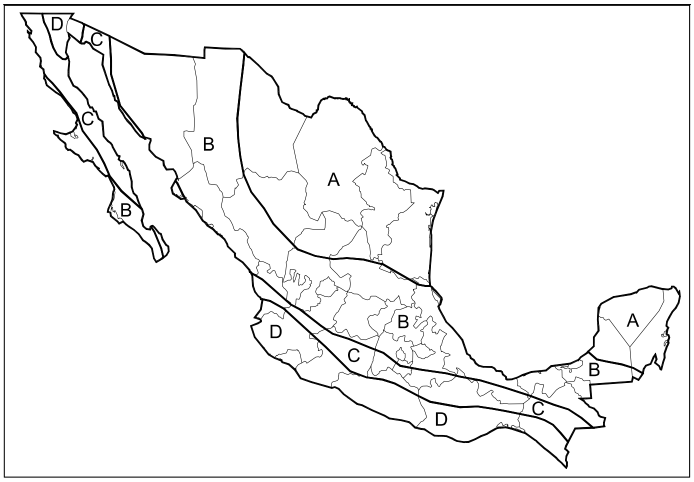
However, the housing characterisation does not distinguish any details related to the construction system and/or the properties that may condition the seismic performance of the building. The word « masonry» is used in a generic way for any kind of stones, ceramic or cement blocks; plus, there is a poor specification for roofing systems. This methodology discusses (but does not involve) the suitability of a more comprehensive typological classification of the constructions. Another relevant limitation can be found in the microseismical zones (Fig. 1). Even if the spectral accelerations of different soil types are considered, this approach does not permit obtaining intensity-based functions for damage, such as damage curves. This limitation is meaningful for developing vulnerability assessments based on different periods of return, restricting some approaches, such as the analysis that considers the constructions' nominal life.

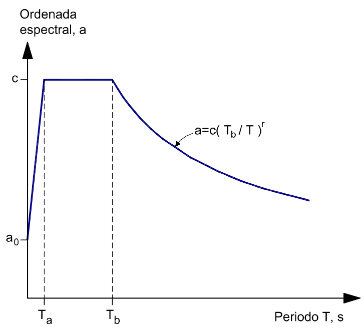
In summary, this simplified approach may be useful for generating a wide and very generalised vulnerability scenario at the level of a municipality or a region but would easily fail to provide detailed information for a building. One of the most interesting aspects of this approach is the incorporation of the social vulnerability together with the physical vulnerability of constructions since there is a series of socioeconomic aspects that fundamentally impact the processes of resilience.

Even though the enhancement of the CENAPRED approach is beyond the scope of the present work, it is pertinent to recognise some positive experiences for enriching local approaches by using complementary tools. For example, Azizi-Bondarabadi et al. [18] depart from an Iranian local parameter-based vulnerability assessment framework, discussing its capabilities and concluding its admissibility. The authors propose the addition of a complementary approach, the GNDT II method, for overcoming some of the limitations found in the original approach, namely those related to the absence of vulnerability curves, then proposing new damage factors specifically calibrated for the study area (associating local damage/cost ratios) and finally coming out with a set of fragility curves to three structural typologies identified among the school buildings. This work demonstrates the feasibility of enriching the Iranian-method index by linking it to a more complex method, which may be adopted in a similar way in the Mexican context.

Table 4
Components for the qualitative assessment of the vulnerability of housing units towards seismic actions.

Concept	Criteria and grading
Vulnerability Index	The result of I_{RF} relates to five so-called "risk levels":
$I_{RF} = I_{vf}\left(0.8 + \frac{I_M}{25}\right)$	$\leq 0.0 \leq I_{RF} < 0.2$ – Very low risk
*The gap between 0.5 and 0.6 seems to be a typographic error of the Guide.	$\leq 0.2 \leq I_{RF} < 0.4$ – Low risk
	$\leq 0.4 \leq I_{RF} < 0.5$ – Medium risk*
	$\leq 0.6 \leq I_{RF} < 0.8$ – High risk*
	$\leq 0.8 \leq I_{RF} \leq 1.0$
Social vulnerability	$I_M = 1$ for very low
I_M, grade of social vulnerability towards disasters. Taken from the municipal classification of the National Institute for Statistics, Geography and Informatics (INEGI).	$I_M = 2$ for low
	$I_M = 3$ for medium
	$I_M = 4$ for high
	$I_M = 5$ for very high
Physical vulnerability	V_i is the grade of the housing unit according to their materials
$I_{vf} = \frac{V_i P_i}{V_p P_m}$	V_p is the housing with the worst performance based on the criteria of V_i
	P_i is the level of seismic exposure in the region of study
	P_m is the maximum possible level of exposure
V_i	$V_i = 1$ for masonry walls with rigid roofing system
According to the materials of the structure	$V_i = 2$ for masonry walls with flexible roofing system
	$V_i = 3$ for adobe walls with rigid roofing system
	$V_i = 4$ for adobe walls with flexible roofing system
	$V_i = 5$ for walls of weak materials with flexible roofing system
V_p	V_p is the maximum possible value for exposure. Therefore, $V_p = 5$
P_i	$P_i = 0.08$ for zona A,
Mexican territory is divided into four major seismic zones: A, B, C, D (Fig. 1).	$P_i = 0.14$ for zone B,
	$P_i = 0.36$ for zone C,
	$P_i = 0.80$ for zone D.
P_m	P_m is the maximum possible value for exposure. Therefore, $P_m = 0.80$





Zona sísmica	Tipo de suelo	a_0	c	T_a	T_b	r
A	I	0.02	0.08	0.2	0.6	½
	II	0.04	0.16	0.3	1.5	⅔
	III	0.05	0.20	0.6	2.9	1
B	I	0.04	0.14	0.2	0.6	½
	II	0.08	0.30	0.3	1.5	⅔
	III	0.10	0.36	0.6	2.9	1
C	I	0.36	0.36	0	0.6	½
	II	0.64	0.64	0	1.4	⅔
	III	0.64	0.64	0	1.9	1
D	I	0.50	0.50	0	0.6	½
	II	0.86	0.86	0	1.2	⅔
	III	0.86	0.86	0	1.7	1

Fig. 1. *Seismic zones according to* Ref. [8].

3.2. The Vulnerability Index Method

The physical damage and loss after a seismic event constitute a very valuable source of information for understanding the behaviour of the structures. This has improved the knowledge on the traditional building technology, anti-seismic empirical or semi-empirical design techniques, the success and failure of building interventions and retrofitting techniques and more recently as valuable data for scientific approaches. The analysis of wide sets of data has allowed correlating meaningful relations between the intensity of earthquakes, some specific characteristics of constructions and the damages they present after a seismic event. The nature of this regressive analysis has allowed identifying several geometrical and material properties that are critical of the seismic vulnerability of traditional masonry building stock, such as for the activation of out-of-plane mechanisms.

The Italian National Group for the Defence from Earthquakes (*Gruppo Nazionale* per *la Difesa dai Terremoti* – GNDT) analysed large sets of data related to the characteristics of constructions that were damaged or lost as the consequence of earthquakes. These analyses allowed identifying essential features that were lately consolidated in a straightforward datasheet [19,20]. This characterisation is based on a series of typological ranges that are common to several cities in Italy but also relatable to other countries across Europe due to the similar traditional construction technology. Despite the inherent difficulties for a generalised mechanical characterisation of masonry, some general assumptions can be made, such as assuming brittle response in tension, frictional response in shear and anisotropy [21]. Hence, it becomes possible to generalise some mechanisms and configurations as the basis for parameter-driven assessments.

The general approach of this method is to consider a set of geometrical and material parameters. Each parameter is then able to be associated with the most suitable of four possible classes (A, B, C and D) that encloses the variability of the parameter assessed. Each parameter is associated with a weight p_i, which represents how crucial/important the characteristic is ruling the seismic performance of the building. For each parameter, the weight is multiplied by the value of the class (c_{vi}), and the weighted sum of all parameters lead to a global vulnerability index [22], as shown in Equation (1). The original proposal considered eleven parameters, but successive adaptations increased that number up to fourteen possible parameters divided into four main groups: structural building system, irregularities and interaction, flooring and roofing systems and conservation status and non-structural elements (see Table 5).

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

As schematised in Fig. 2, in which the circumference has been proportionally divided according to the weight of each parameter, certain aspects of the construction are significantly more determinant than the rest, such as parameters BP1 and BP2. The concentric circles are also proportional to the numerical value according to the class. It is convenient to keep in mind that the progression between classes can be more significant between classes C and D. If the area of the entire circle is 650 units and the regions are shaded according to the grade of each parameter, then it graphically represents the true value of I_{vf}^{*} as a proportional shaded surface.

This method has been applied to numerous case studies, such as the ones of Coimbra [13,24], Seixal [25], Horta [23] and Leiria [26], Portugal; Annaba, Algeria [27]; Timișoara, Romania [28]; Osijeck, Croatia [29] etc., demonstrating the suitability of this approach to be adapted based on adjustments of the weights and damage curves according to the typological characteristics [30]. The concerns related to the constraints for accomplishing an extensive survey (e.g., not having complete access to the building site or drawings) encouraged the design of a complementary façade scale evaluation approach. This method is mostly focused on the potential assessment of out-of-plane mechanisms (by assessing building features that make them more prone to such) and was widely explored initially [31], that proposed an initial set of 10 parameters that have been expanded in the following years [32–34]. The logic and procedures behind this method are the same that those applied for the building scale method, considering a total of 13 parameters (see Table 6).

Table 5
Vulnerability Index parameters, according to the calibration of [23].

Parameters	Class (C_{vi})				Weight (p_i)	Relative weight
	A	B	C	D		
Group 1. Structural building system						50/100
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
Group 2. Irregularities and interaction						20/100
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
Group 3. Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	4.91
BP12. Roofing system	0	5	20	50	2.00	13.09
Group 4. Conservation status and other elements						12/100
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

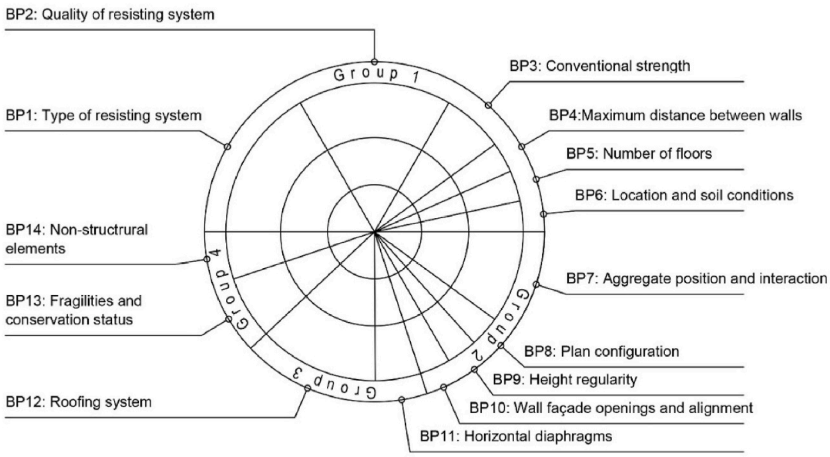


Fig. 2. Schematic representation of the parameters and their weight.

Table 6
Parameters and vulnerability classes, according to Ref. [34].

Parameters	Class, C_{vi}				Weight	Relative weight
	A	B	C	D	P_i	
Group 1. Façade geometry, openings and interaction						16.7/100
FP1. Geometry of façade	0	5	20	50	0.50	
FP2. Maximum slenderness	0	5	20	50	0.50	
FP3. Area of openings	0	5	20	50	0.50	
FP4. Misalignment of openings	0	5	20	50	0.50	
FP5. Interaction between continuous façades	0	5	20	50	0.25	
Group 2. Masonry materials and conservation						31.5/100
FP6. Quality of materials	0	5	20	50	2.00	
FP7. State of conservation	0	5	20	50	2.00	
FP8. Replacement of original flooring system	0	5	20	50	0.25	
Group 3. Connection efficiency to other structural elements						33.3/100
FP9. Connection to orthogonal walls	0	5	20	50	2.00	
FP10. Connection to horizontal diaphragms	0	5	20	50	0.50	
FP11. Impulsive nature of the roofing system	0	5	20	50	2.00	
Group 4. Conservation status and other elements						18.5/100
FP12. Elements connected to the façade	0	5	20	50	0.50	
FP13. Improving elements	0	5	20	50	−2.00[a]	

[a] The negative weight mathematically reflects the positive impact of the improving elements in terms of vulnerability reduction.

Although the identification of the characteristics that critically determine the seismic vulnerability is very dependent on typological similarities, it is possible to admit a certain level of similarity among historical constructions in determined contexts. For example, Mexican housing constructions in historical centres are typologically related to the use of local materials and traditional construction techniques and solutions that are also common in European countries. The Viceroyalty of New Spain (1521–1821) represents a period in which a permanent exchange of architectonic and urban tendencies moulded the physiognomy of the (now) historical cities in Mexico. These constructions have numerous technical and construction similarities with their chronological counterparts in the Iberian Peninsula. This cultural bridge is a strong indication that this approach can be suitable to assess the historical constructions in the Mexican urban context.

A limitation, however, is that the criteria and analysis for the parameters are strongly focused on typological constants of the European constructions. This situation does not hinder the application to the Mexican building stock. However, the description and grading of all the parameters are needed in order to facilitate an objective framework for its application. The works of Salazar and Ferreira [35] explored the assessment of buildings in the historical neighbourhood of La Merced in Mexico City by using the Vulnerability Index Method approach. This experience established a set of typologies (four geometrical types and nine material types) for generalising a set of 166 constructions (however, several limitations are implicitly present when assuming generalisations throughout a sample). This typological approach was potentially limited, for example, when there are morphological modifications due to building interventions (interior space changes, refurbishments, etc.). In this context, the analysis of individual buildings instead of groups is still a gap in literature addressed to Mexican assets.

It is worth highlighting that this approach has also been used as a conceptual basis for developing more specific methods, such as the Seismic Vulnerability Index for Vernacular Architecture (SVIVA), developed by Ref. [36]. The SVIVA formulation includes a definition of the parameter's vulnerability classes according to numerical reference models. The relative weight of each parameter was obtained using multiple linear regression and expert opinion. Although this approach was initially targeted at Portuguese vernacular architecture, the authors admit its applicability to similar structures outside the Portuguese context. In fact, it is plausible to assume that this approach would also be suitable to analyse the present case of study. The main reason for adopting here the Vulnerability Index Method proposed by Ferreira et al. [23] lies in the fact that the vulnerability parameters are more explicitly unfolded in this method. Despite that, the data generated in this work can likely be used to generate vulnerability results with the SVIVA approach, providing, therefore, a good base for future works of validation or numerical calibration based on the effects of the 2017 earthquakes in the Mexican constructions.

Data availability for single buildings is a very relevant challenge for applying the Vulnerability Index Method to large sets of constructions. However, the Mexican context provides an advantage due to the existence of the National Catalogue of Historical Monuments. Developed by the National Institute for Anthropology and History (*Instituto Nacional de Antropología e Historia, INAH*), this catalogue is a valuable resource that groups more than 100,000 datasheets that individually describe historical monuments in Mexican territory. Since Mexican law determines that any construction built before the year 1900 must be considered as a historical monument [37]), the constructions covered by this catalogue is wide.

The experiences of Ramírez Eudave and Ferreira [38] provided a first insight on the use of this catalogue for feeding the Vulnerability Index Approach, supporting its suitability by comparing the expected damages and the effects of the 19th of September 2017 earthquakes in Atlixco, Puebla, that had a Modified Mercalli Intensity of 7.5 in this city (USGS 2017). This city is a representative case of a Mexican historical city centre, recognised as a Zone of Historical Monuments (*Zona de Monumentos Históricos*) by the INAH. This denomination is given due to a relevant concentration of historical monuments and provides a special framework for its safeguarding. Even if the proof-of-concept study was based on a limited set of nine constructions, it strongly suggests the suitability of the methodology for assessing Mexican constructions. Although the catalogue ideally covers almost all the parameters to be used by the Vulnerability Index Method, this experience also found a strong limitation since most of the datasheets is incomplete. A more extensive and comprehensive experience was possible in the scope of a series of surveys performed in the previous months before the 2017 earthquakes.

4. Materials and methods: the dataset

A comprehensive catalogue for the historical monuments of the city of Atlixco, Puebla, following the model of the INAH datasheet, was used by Martínez, Ruíz, Tototzintle and Flores [39–42] and within the scope of their work an improved datasheet was made (see Fig. 3) that contains additional and valuable information fields, such as general measurements and façade drawings (see Table 7). These works were mostly developed in the months that preceded the earthquakes of September of 2017, giving a valuable testimony of the general conservation state of the constructions in a pre-damage stage. Furthermore, some of the datasheets also include descriptions of the damages suffered because of the earthquakes. The use of this information allowed to significatively enlarges the first insight on the use of the Mexican Catalogue by applying the Vulnerability Index Method approach to a total of 83 constructions.

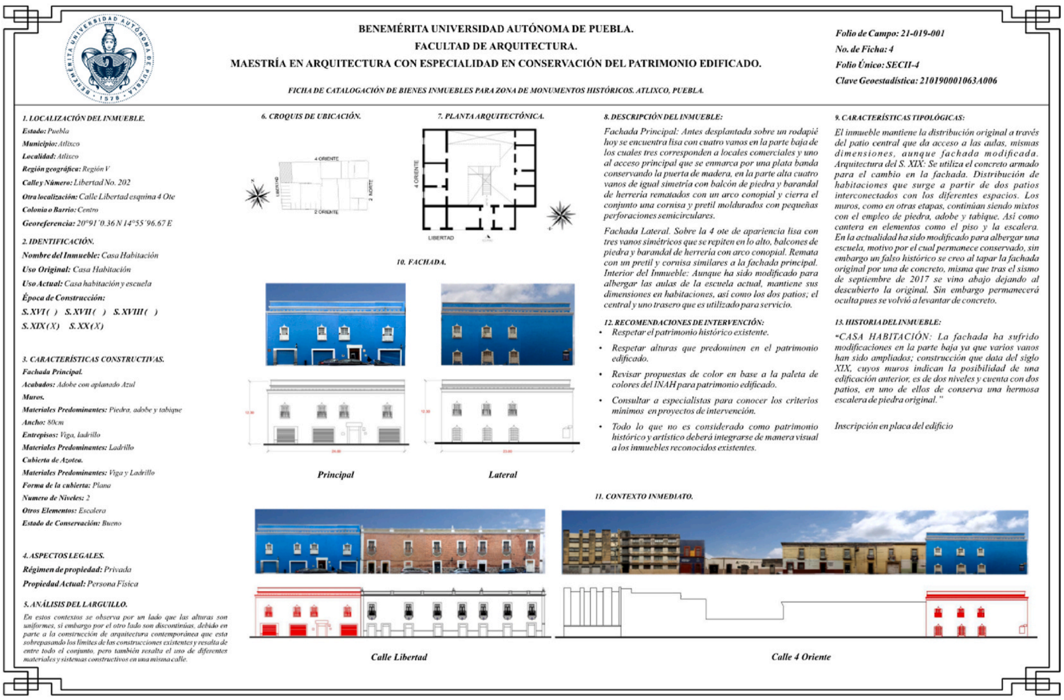


Fig. 3. *Example of a datasheet (in Spanish). Extracted from* Ref. [42].

Table 7
Fields considered in the datasheets of Martínez, Ruíz, Tototzintle and Flores [39–42]

Field	Content of the field	Field	Content of the field
F0	Key/Building code	**F9**	Legal aspects. Regime of property.
F1	Site and Location: State, Municipality, Settlement, Region, Street and number, coordinates.	**F10**	Façades of the entire block front
F2	Identification. Name, original use, present use, the century of construction.	**F11**	Location (map). (Isolated, Corner, Row Building, End-row building)
F3	Construction characteristics of the main façade: Finishing/Coverings	**F12**	Architectonic plan (ground floor).
F4	Construction characteristics of the walls: Predominant materials and thickness.	**F13**	Drawings and photo rendering of the façades of the block.
F5	Construction characteristics of the floor diaphragms: Predominant materials.	**F14**	Description of the building.
F6	Construction characteristics of the roofing systems: Predominant materials, geometry.	**F15**	Interventions recommended.
F7	Number of floors	**F16**	Typological characteristics.
F8	State of conservation (Good; Regular; Poor).	**F17**	History of the building.

The very first step of this work involves the assessment of the seismic vulnerability of these 83 buildings, before the 2017 quake, resourcing to data (geometrical and material characteristics) comprehensively documented in the National Catalogue of Historical Monuments, which were compiled shortly before the 2017 event. The vulnerability index associated with each building assessed is then used to estimate a damage grade for an earthquake with the intensity of that of the September 2017 event. Finally, this predicted mean damage is compared with the observed damages that the buildings suffered in order to assess the reliability of the method, identifying limitations that could drive improvements and corrections to the approach.

The buildings assessed in this study share typological characteristics and traditional construction techniques that are often found in traditional residential buildings in the historical centres of the region, namely in the states of Puebla, Mexico and Morelos. Buildings with no more than three storeys, with spaces organised around patios, flat roofing systems, load-bearing masonry walls (different quality), are the most common ones. The buildings assessed represent 67% of the catalogued monuments of the city, given that there were numerous buildings excluded due to the following reasons:

- Identification of data inconsistencies found in the datasheet, namely between photos and drawings;
- Incomplete information in the datasheets;
- The building has too many structural changes;
- The structure is typologically singular. The parameters considered in the method are not applicable (this situation frequently occurs when dealing with churches).

It is noteworthy to state that the results and conclusions herein presented are constrained by the limits of the representativeness that the buildings in Atlixco have in the Mexican context. Nevertheless, no relevant typological singularities were found throughout the universe of studied buildings when compared to common masonry constructions found in the central region of Mexico. A sine *qua non-condition* for applying this method is to assure the fitting of the building characteristic regarding the parameter's grade condition given in Annex 1; this work is based on the premise and hypothesis of the applicability of the method to any construction typologically framed with similar, traditional construction technology, geometrical and material conditions.

4.1. Parameters and grading for Atlixco: Building scale approach

During the analysis of these datasheets, it was found that the descriptions of the parameters approach may need to be contextualised for adequately grading the vulnerability classes and fully describing the characteristics contained in the datasheets. A semantical and typological analysis was made in order to identify some potential sources of uncertainty or divergence between the Vulnerability Index Method and the structure and data given by the datasheet information, which is based on the original structure of the INAH database. Both approaches, the one for the building and the one for the façade, were analysed. The criteria followed and adopted for the building scale is from Vicente [31]. A full description of the 13 parameters (BPi), including a short discussion regarding the specific conditions that have been considered for dealing with the necessary adaption to apply these approaches, is given in Annex I. A list of criteria for the façade approach proposed by Ref. [31] is also discussed and enriched with the considerations of [24] for those parameters that were not considered in the previous versions of the approach.

4.2. Comparison between observed and analytical damage grade obtained with the Vulnerability Index Method

Once obtained a vulnerability index for the buildings, it is possible to estimate levels of damage for different intensity events. These damage functions involve some additional parameters, such as a ductility factor for the construction Q = {1:4} and the macroseismic intensity in the IEMS-98 scale. These parameters, together with a normalised vulnerability value V (Eqs. (2) and (3)), allow one to estimate a mean damage grade μ_D [26] that can range from 0 up to 5 (Eq. (4)), including a correction factor introduced when the seismic intensity is $I \leq 7$ (Eq. (5)). Previous experiences, such as the one of [34], have explored the qualitative correspondence existing between values for μ_D and the discrete damage grades (D_k) defined in the EMS-98 scale [43], based on the macroscopic evidence of damage. This correlation also facilitates the inclusion of damage factors (*DF*) that represent the cost of repairing a construction (Eq. (6)). The damage factors herein adopted are those proposed by Ref. [44]. The correspondences among mean damage grades, damage factors and discrete damage grades are shown in Table 8.

Table 8
Correlation between discrete damage grades and ranges of mean damage grade.

Discrete damage grades, D_k	Damage factors *DF*	Range for the mean damage grades, μ_D	
		μ_D^-	μ_D^+
D_0 – No damage. No observed damage.	0.00	0.00	0.50
D_1 – Slight damage. Presence of very localised and hairline cracking.	0.01	0.50	1.42
D_2 – Moderate damage. Cracks around openings; localised detachment of wall coverings (plaster, tiles, etc.).	0.10	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.	0.35	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.).	0.75	3.50	4.00
D_5 – Destruction. Total in-plane or out-of-plane failure of the façade wall.	1.00	4.00	5.00

These expressions are discussed on the proposal of [45], where the levels of damage are contextualised in a mixed numerical and conceptual framework by using linguistic terms together with the fuzzy set and the probability theory. This work put forward probabilistic vulnerability classes for different building types defined according to structural criteria. It is worth mentioning that the vulnerability models proposed by Lagomarsino and Giovinazzi [45] are specifically thought to fit the European built environment. However, the use of a more generic structural classification opens the door to possible extrapolations of the procedure, despite the limitations of using a linguistic-based judgement.

All the constructions were primarily assessed for obtaining a D_k value corresponding to the post-event damages. This assessment was performed by means of two approaches. The first approach was based on the images and observations contained in those datasheets produced after the earthquake. Therefore, this information is considered a primary source of information. When datasheets were produced before the earthquake, observations were based on images of the post-event scenario taken and made available through media channels and Google Maps imagery. Those buildings whose post-event state was not documented were not considered in the scope of this study.

$$I_v = \frac{I_v^* \times 100}{750} \tag{2}$$

$$V = 0.592 + 0.0057 \times I_v \tag{3}$$

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

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

$$\mu_D = 5 \times DF^{0.45} \tag{6}$$

The macroseismic intensity estimated by the United States Geological Survey for the 19th of September 2017 earthquake in Atlixco [46], reported with a value of 7.5 in the Modified Macroseismic Intensity (MMI) scale, is taken in this work. Plus, the equivalence of MMI and EMS-98 scales, discussed by Ref. [47], has been assumed. The ductility factor for performing the assessment is that considered by the Complementary Technical Code for Seismic Design of the Building for Mexico City [48], that is often considered as a national standard for seismic design. This code recommends adopting a ductility value of $Q = 1.0$ for unreinforced masonry structures, regardless of whether the masonry is composed of brick or stone units. This is due to the lack of more specific criteria on the regulations and experimental data for this sample. This indicative value is conservative and can and should be discussed and adjusted when new evidence is available.

4.3. The role of uncertainties in the assessment process

As in any assessment method, it is imperative to be aware of the sources of uncertainty that may affect the results. Therefore, it is convenient to specify in the context of the present work some of the more relevant uncertainties found during this process. Some of these uncertainties have an epistemic nature, i.e., result from lack of information, simplifications or biased decisions that need to be made during the process. An intrinsic source of uncertainty when dealing with parametric-based methods lies in the semantic description of the parameters, which often leave room for interpretation (a frequent challenge when performing qualitative assessments). Another relevant source of uncertainty inherent to the method is the discretisation of the parameter's grades, namely in those situations where qualitative or quantitative criteria are close to thresholds. This can happen even when the information available is enough detailed for grading all the parameters. Finally, a relevant source of uncertainty is associated with situations of lack of information and where there is an inability to grade a particular parameter accurately.

Table 9
Example of conservative grades obtained after combining different grades and QC levels.

Parameter	Grade	QC	Action		Conservative grade
BP1	A	QC1	Remains the same	➔	A
BP2	B	QC0	Remains the same	➔	B
BP3	C	QC2	One-step downgrade, if possible	➔	D
BP4	D	QC3	Two-step downgrade, if possible	➔	D
BP5	B	QC1	Remains the same	➔	B
BP6	C	QC2	One-step downgrade, if possible	➔	D
BP7	D	QC1	Remains the same	➔	D
BP8	B	QC0	Remains the same	➔	B
BP9	A	QC3	Two-step downgrade, if possible	➔	C
BP10	D	QC1	Remains the same	➔	D
BP11	C	QC2	One-step downgrade, if possible	➔	D
BP12	D	QC2	One-step downgrade, if possible	➔	D
BP13	C	QC1	Remains the same	➔	C
BP14	B	QC3	Two-step downgrade, if possible	➔	D

The use of the updated catalogue for Atlixco represents a privileged opportunity for performing a comprehensive assessment based on recent information. Nevertheless, there are some situations in which the information found in this source hinders being insufficient for accurately grading a determinate parameter. This situation can happen because of a series of situations, such as low-resolution figures (floorplans or photos), semantical divergence (on the use of unprecise descriptions of masonry works), subjective undefined observations, or lack of data. Therefore, an additional grading was introduced with the objective of assessing the reliability of the vulnerability class assigned to a determinate parameter.

This grading, named Quality Check (QC), was conceptualised for accomplishing two fundamental purposes. Firstly, it allows identifying which parameters were accurately assessed and which ones are based on relatively weak assumptions, favouring a straightforward enhancement of the database by addressing specific aspects of the survey. Secondly, it also allows assuming a more conservative approach towards the lack of information. Even in the cases where all the parameters in which the existing data was considered as insufficient were reasonably assessed by means of experience and engineering judgement, the QC grading facilitates the calculation of an alternative vulnerability index by accepting that certain parameters can receive a more unfavourable condition that the originally assumed. The QC grading considers four different levels of accuracy and quality of information, namely:

- QC0: High quality. Grade verified with a high level of certainty. Data is explicitly contained on the datasheets and have been verified in-situ or by more than two sources (e.g., press and/or Google Maps).
- QC1: Medium quality. Deduced from secondary sources, (photographs, drawings, testimonies, etc).
- QC2: Low quality. Reasonably based on typological similarities and hypothesis based on experience.
- QC3. Absence of information. The grade is merely indicative but still better than a random decision.

For this study, each construction received two sets of parameter grading. The first one corresponds to the grade assignation regardless of the QC level. The second one modifies this assessment according to the QC level if a parameter is associated with QC2 or QC3 levels. A specific parameter with a QC2 classification will receive a more conservative vulnerability class (i.e., from A to B, B to C or C to D), while QC3 will imply a two-level downgrade (i.e., from A to C and B to D). All the parameters with QC0, QC1 and those that cannot receive the corresponding downgrade (e.g., a parameter graded with D with a QC2) remain unchanged, as presented in Table 9.

This approach has been found useful for expressing mean damage grades as a range instead of a nominal value. It is assumed that the interval between the original and conservative assessments (upper and lower bounds) reasonably cover the real conditions of the construction – the larger the uncertainty, the larger the interval for the mean damage grades, μ_D. This approach is considered feasible and suitable given that the observed damage is, in fact, associated with an interval of μ_D, rather than discrete values, D_k. Then, any discrete level of damage is intrinsically associated with a lower and an upper bound as well. Therefore, the approach proposed in this work is based on a range-based analysis where the accuracy of the results is given by the overlap of the ranges, not only by the proximity between the observed damage and the analytical values of the mean damage grade.

5. Results and discussion

While carrying out the seismic assessment, it was noticed that the uncertainty was mainly concentrated in parameters BP6, BP9, BP11 and BP12. This was expected due to the poor information available for assessing the soil conditions (BP6), often limited to slope and the criterium of having a regional rock soil considered for the whole site. Parameter BP9 accumulated some uncertainties when assessing buildings that presented signs of modifications, namely with additions in the upper plans. Since references to diaphragms and roof systems are limited, BP11 and BP12 (floor slabs and roofs) are associated with a certain generalised uncertainty when the existing images do not allow to have a clear perception of the structural system. As shown in Fig. 4, there is a generalised low grading of the vulnerability class in the case of parameters BP2 and BP3, which can be partially explained by the poor masonry fabric of rubble stone and the conservative values adopted for assessing the loads and the characteristic compressive strength of masonry.

Some cases were especially difficult to assess since their typologies are not explicitly described within the method. Samples SECII-10, SECIII-1, SECIII-3, SECIV-1, and SECIV-2 are very illustrative examples, corresponding to buildings that are also galleries covering

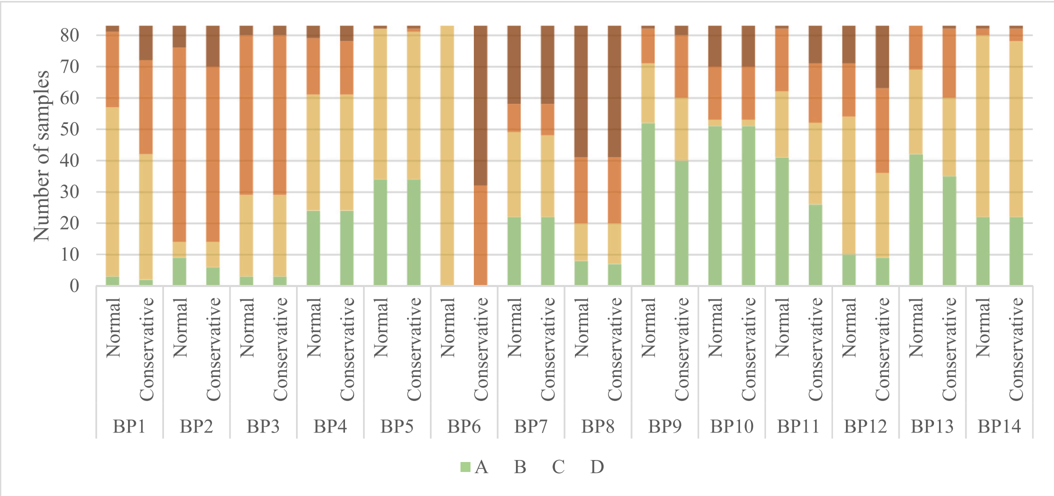
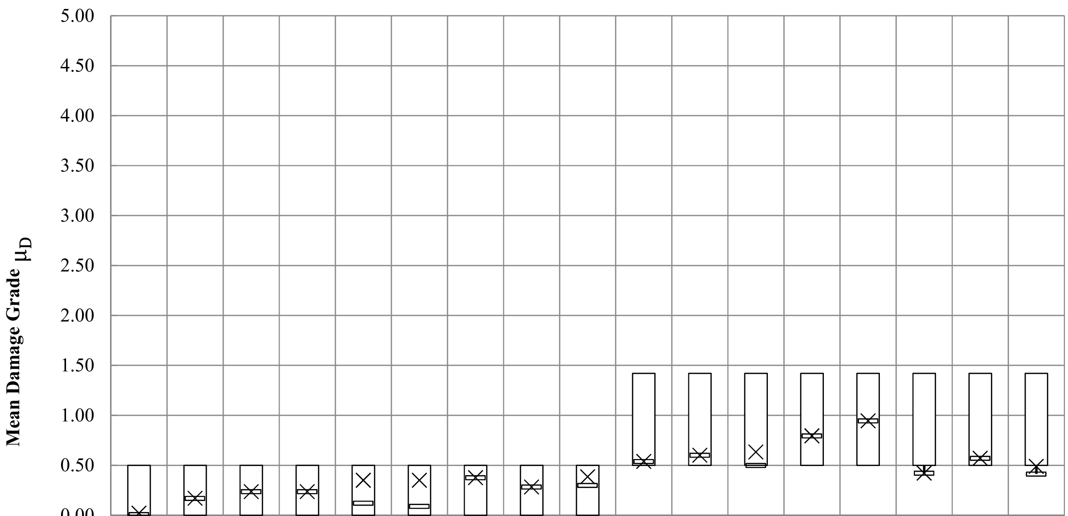


Fig. 4. Vulnerability class grading distribution by parameter, considering the original and conservative approaches.

the pavements. The methodology led to conservative results, i.e., to analytical mean damage grades higher than the observed in the buildings. Figs. 5–9 contains a summary of the mean damage grade (μ_D) for each building according to the simple and conservative approaches in contrast to the lower and upper bounds that correspond to the observed discrete damage grade attributed after the seismic event.

The mean damage grade value among the sample was $\overline{\mu_D} = 1.28$ ($\sigma = 1.0$) with extreme values $\mu_{D,\ max} = 4.94$ and $\mu_{D,\ min} = 0.01$, while the conservative mean damage presented $\overline{\mu_{Dcons}} = 1.79$ ($\sigma = 1.25$) with extreme values $\mu_{Dcons,\ max} = 4.94$ and $\mu_{Dcons,\ min} = 0.02$. The Kolmogorov-Smirnov test was performed to assess the distributions' normality for both, μ_D and μ_{Dcons} values. For both series of results, the normality hypothesis H_0 is not supported at a significance level $\alpha = 0.05$, obtaining *P*-values of 3.59×10^{-6} for μ_D and 9.89×10^{-4} for μ_{Dcons}.The results, in fact, are significatively skewed to the left.

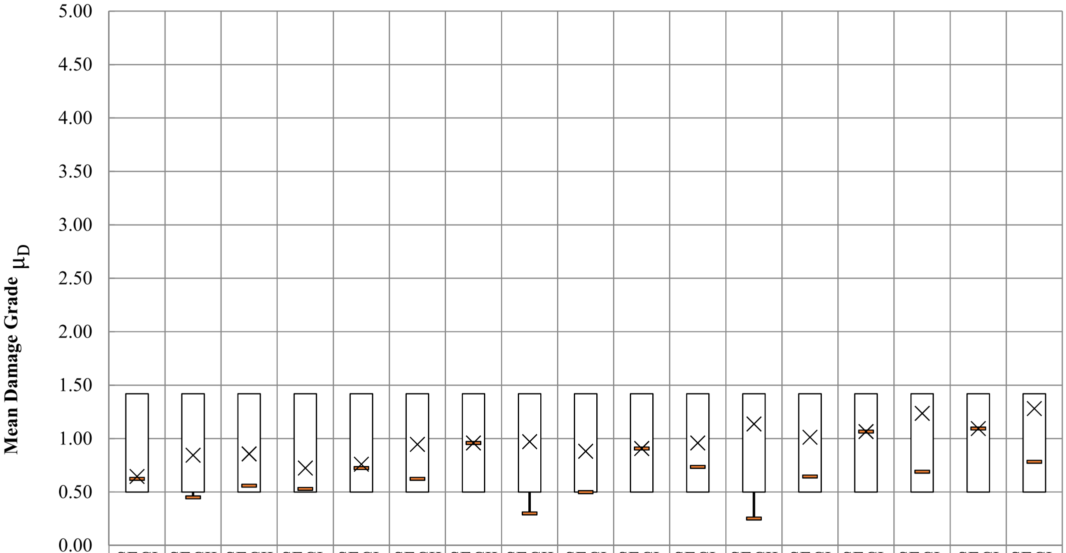
For both assessments, samples SECI-24 and SECIII-16 presented the highest and lowest mean damage grade value, respectively. These figures also present the μ_D^- and μ_D^+ that respectively correspond to the level of damage observed in the building, according to the



	SECII I-16	SECI V-7	SECII I-27	SECII I-30	SECII -18	SECII I-3	SECI V-6	SECII I-10	SECII I-25	SECI V-2	SECI V-1	SECI V-19	SECII I-2	SECII I-1	SECII -9	SECI V-5	SECII I-28
μ_D-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
μ_D	0.01	0.17	0.24	0.24	0.12	0.09	0.38	0.28	0.30	0.54	0.60	0.50	0.80	0.95	0.42	0.57	0.41
μ_Dcons	0.02	0.17	0.24	0.24	0.35	0.35	0.38	0.28	0.39	0.54	0.60	0.63	0.80	0.95	0.42	0.57	0.49
μ_D+	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42

μ_D ×μ_Dcons

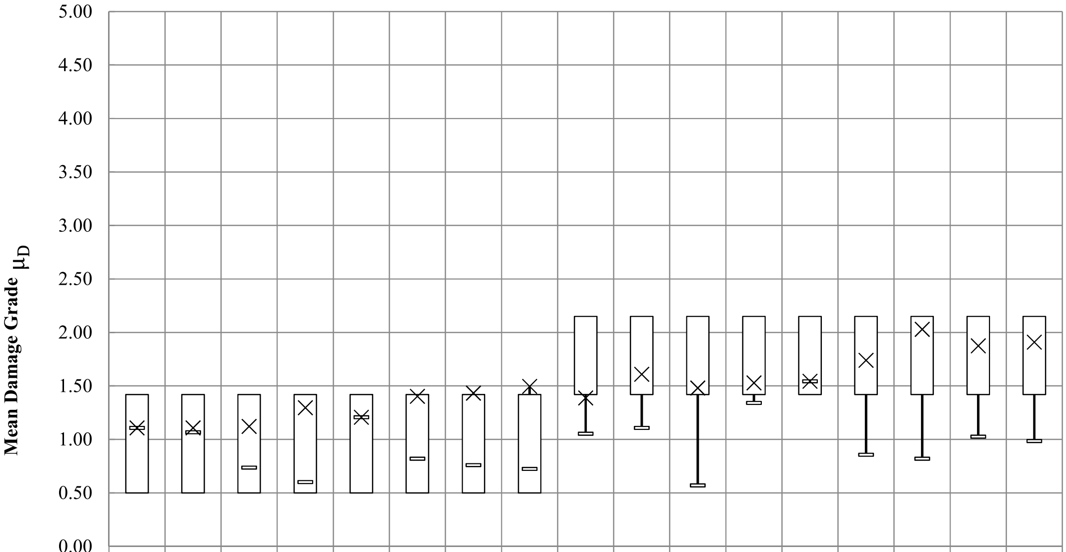
Fig. 5. Summary of results (part 1 of 5). The interval between μ_D^- and μ_D^+ is represented as the white box.



	SECIV-21	SECII I-26	SECII I-11	SECI-84	SECI-69	SECII I-12	SECII I-22	SECII I-13	SECI V-4	SECI-67	SECI-70	SECII -2	SECI V-15	SECI-64	SECI-85	SECI V-20	SECI-113
μ_D-	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
μ_D	0.62	0.45	0.56	0.53	0.72	0.62	0.96	0.30	0.50	0.91	0.74	0.25	0.65	1.07	0.69	1.09	0.78
μ_Dcons	0.65	0.84	0.86	0.72	0.76	0.95	0.96	0.97	0.88	0.91	0.96	1.14	1.01	1.07	1.24	1.09	1.28
μ_D+	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42

- μ_D × μ_Dcons

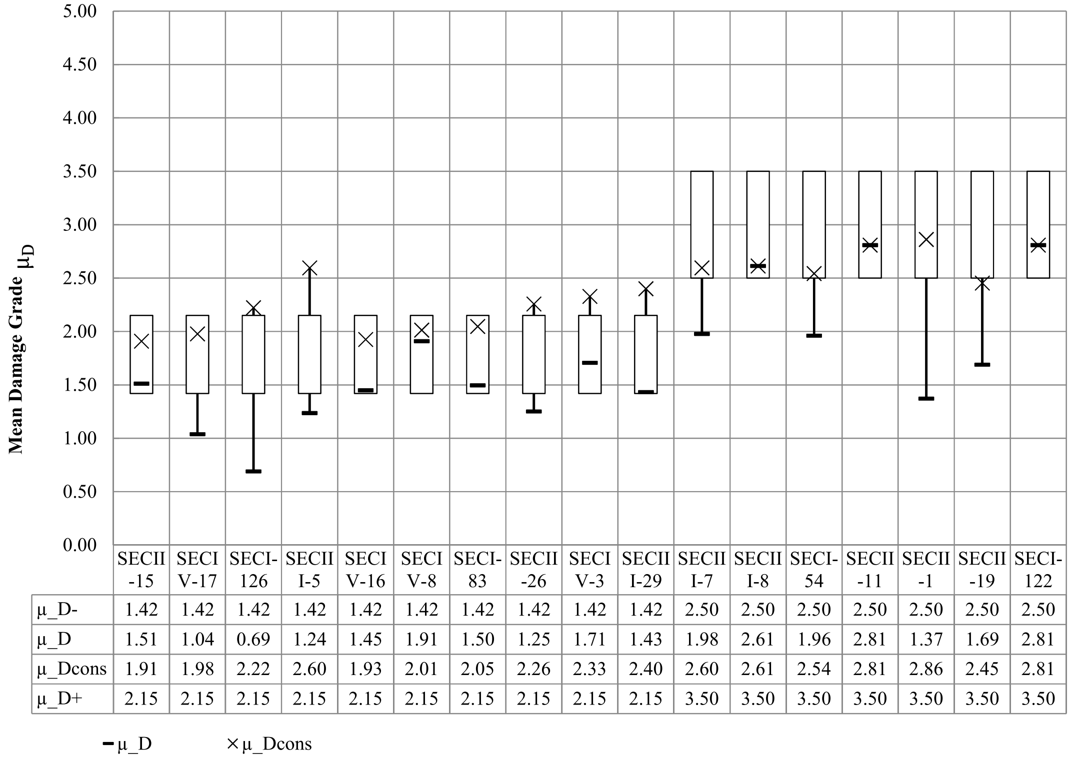
Fig. 6. Summary of results (part 2 of 5). The interval between μ_D^- and μ_D^+ is represented as the white box.



	SECI-123	SECI V-24	SECII -20	SECII I-24	SECII I-21	SECII I-20	SECII -3	SECII -4	SECII -29	SECI-114	SECI V-11	SECII -6	SECII -22	SECII I-19	SECI-82	SECII -24	SECI V-23
μ_D-	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
μ_D	1.11	1.07	0.74	0.60	1.21	0.82	0.76	0.72	1.05	1.11	0.57	1.34	1.54	0.86	0.82	1.03	0.99
μ_Dcons	1.11	1.11	1.12	1.30	1.21	1.40	1.43	1.50	1.39	1.61	1.48	1.53	1.54	1.74	2.03	1.87	1.91
μ_D+	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15

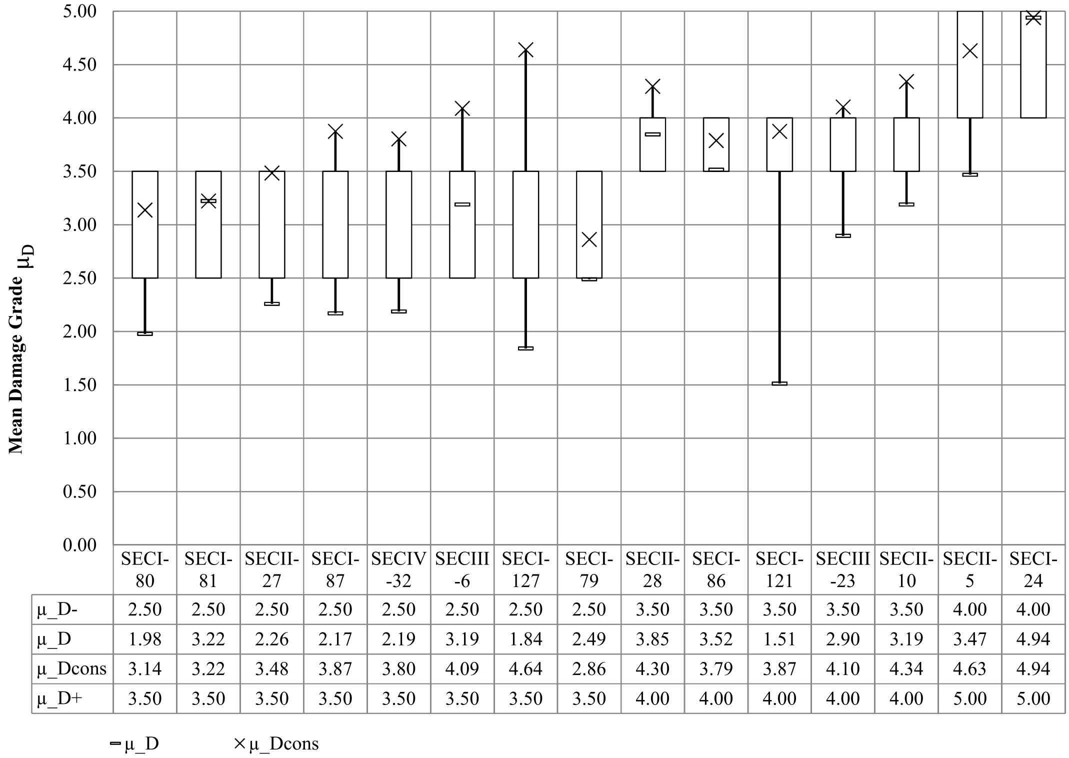
- μ_D × μ_Dcons

Fig. 7. Summary of results (part 3 of 5). The interval between μ_D^- and μ_D^+ is represented as the white box.



	SECII-15	SECIV-17	SECI-126	SECIII-5	SECIV-16	SECIV-8	SECI-83	SECII-26	SECIV-3	SECIII-29	SECIII-7	SECIII-8	SECI-54	SECII-11	SECII-1	SECII-19	SECI-122
μ_D-	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	2.50	2.50	2.50	2.50	2.50	2.50	2.50
μ_D	1.51	1.04	0.69	1.24	1.45	1.91	1.50	1.25	1.71	1.43	1.98	2.61	1.96	2.81	1.37	1.69	2.81
μ_Dcons	1.91	1.98	2.22	2.60	1.93	2.01	2.05	2.26	2.33	2.40	2.60	2.61	2.54	2.81	2.86	2.45	2.81
μ_D+	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	3.50	3.50	3.50	3.50	3.50	3.50	3.50

Fig. 8. Summary of results (part 4 of 5). The interval between μ_D^- and μ_D^+ is represented as the white box.



	SECI-80	SECI-81	SECII-27	SECI-87	SECIV-32	SECIII-6	SECI-127	SECI-79	SECII-28	SECI-86	SECI-121	SECIII-23	SECII-10	SECII-5	SECI-24
μ_D-	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	3.50	3.50	3.50	3.50	3.50	4.00	4.00
μ_D	1.98	3.22	2.26	2.17	2.19	3.19	1.84	2.49	3.85	3.52	1.51	2.90	3.19	3.47	4.94
μ_Dcons	3.14	3.22	3.48	3.87	3.80	4.09	4.64	2.86	4.30	3.79	3.87	4.10	4.34	4.63	4.94
μ_D+	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	4.00	4.00	4.00	4.00	4.00	5.00	5.00

Fig. 9. Summary of results (part 5 of 5. The interval between μ_D^- and μ_D^+ is represented as the white box.

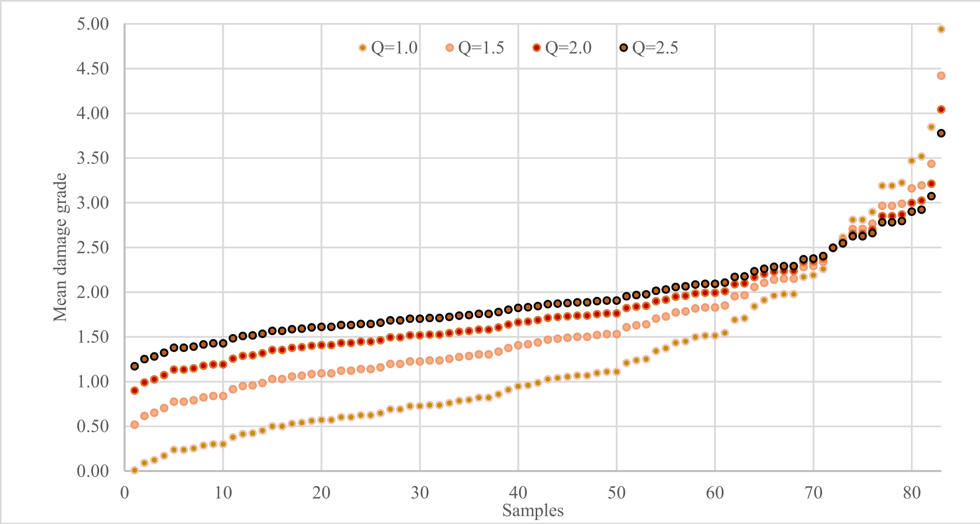


Fig. 10. Variability of the Mean damage grades for the 83 constructions by using different values of ductility Q (The buildings were arranged from the lowest up to the highest mean damage grade value).

criterium explained in Table 8. This representation illustrates the overlap between the intervals of the mean damage grade obtained from the vulnerability index of the building and the actual level of damage suffered by the building.

When the ranges of the mean damage grades and the real discrete damages are plotted together, it is evident that a vast majority of values present an overlap. This is meaningful because it reveals a level of consistency towards the whole assessment. It is convenient to consider that the proportion of this overlap depends on numerous circumstances, such as the amplitude of the range for the discrete D_k values and the accumulation of uncertainties during the assessment process. Nevertheless, the tendencies exhibit a satisfactory pattern of proportionality and coherence. It is worth noting that there can be a relevant distortion when dealing with the boundaries of the discrete damage values, given that the same semantical description may cover a wide variety of damages and patterns. This has been recognised as a potential limitation for using and calibrating this method, opening the possibility of developing more objective strategies for assessing damages in post-seismic scenarios.

Furthermore, it is important to mention that these results depend on the definition of the ductility factor, Q1, assumed equal to 1. Although this is the value suggested by the Mexican code for unreinforced masonry, the adoption of a ductility factor value based on experimental evidence is a most desirable improvement for any application of the method to any case. As shown in Fig. 10, there can be a relevant variation in the mean damage grades for some building cases, namely the ones with the lowest and highest mean damage grades. Adopting different values for the ductility factor, for example, a less conservative value, i.e., a value higher than the Q = 1.0 considered here, will reduce the global dispersion of the mean damage grades of the set of buildings assessed.

Although the mean damage grade values are important references for single-building qualitative assessment, it is possible to offer a contextualisation for an entire group of buildings, typologically similar in the same affected site, by means of a cartesian uncertainty/mean damage grade map. This representation facilitates the correlation between the distribution of the uncertainty level and the level of damage throughout a series of constructions, easily identifying how reliable the assessment of the vulnerability class is. Since this map offers a contextualised comparative, it becomes possible to hierarchise further surveys (e.g., on those buildings that apparently present a high mean damage grade value combined with relatively high uncertainty) and even immediate remedial actions (e.g., on those constructions that combine a relatively low uncertainty and a high mean damage grade.

In order to do so, the uncertainty has been graded by imposing numerical values associated with the levels: QC0 = 0; QC1 = 0.33; QC2 = 0.67; QC3 = 1.00. The uncertainty index *UI* is given by the sum of the value of the QC corresponding to each parameter multiplied by the weight that the parameter has in the seismic vulnerability method. Hence, uncertainty is proportional to the impact of the parameter. Finally, the result is divided by 15 (the sum of all **(**p_i) partial weights) in order to have a normalised value from 0 to 1, in which 1 represents an absolute uncertainty of all parameters.

$$UI = \frac{\sum_{i=1}^{14} QC_i \times p_i}{15} \; \{0, 1\} \tag{5}$$

The upper and lower limit values for this index were a minimum $UI_{min} = 0.07$ for sample SECIII-16, a maximum $UI_{max} = 0.54$ for sample SECII-29 respectively and a mean of $\overline{UI} = 0.37$ with a standard deviation $\sigma = 0.08$. This approach would facilitate the identification of the buildings assessed that combine a low quality of information but seem to have an elevated vulnerability index, becoming cases for further detailed appraisal and assessments. On the other hand, a combination of a low uncertainty index and a low mean damage grade is desirable. The thresholds for this representation can be decided, for example, according to ranges of acceptability in terms of repair costs, establishing criteria for risk acceptability. Fig. 11 presents an example based on the universe herein discussed .

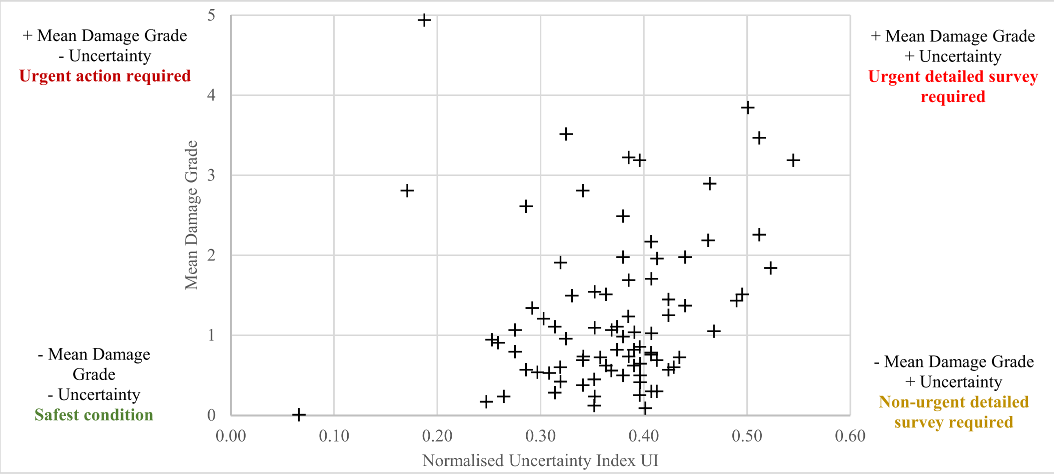


Fig. 11. Distribution of the sample according to the calculated mean damage grade against the uncertainty index.

The samples close to the bottom-left corner combine relatively low mean damage grades and low uncertainty, which is the safest condition in the context of the urban assessment. In contrast, samples in the dominion of the top-left corner combine relatively high mean damage grades with a relatively low degree of uncertainty. This means that these buildings are more likely to present a poor seismic performance – due to their high seismic vulnerability – and, consequently, deserve the most immediate attention. Samples in the top-right dominion present a high mean damage grade and relatively high uncertainty. This may indicate that the damage grade is amplified by the lack of reliable information. These buildings deserve particular attention as well, namely by carrying out urgent surveying actions devoted to double-checking their vulnerability, potentially resorting to more detailed assessment methodologies. Finally, the points closer to the bottom right corner of the graph refer to low vulnerable buildings. Although relatively high levels of uncertainty are associated with these buildings, their reassessment is not a priority, given that they are unlikely to suffer significant levels of damage. As is easy to understand for this analysis, this type of representation helps prioritise interventions, allowing for more efficient and rational use of the available resources.

Table 10 summarises the distribution of damage grades throughout the studied universe. The numerical values associated with the uncertainty are used for calculating mean values for the 83 constructions assessed. These mean values UI_p are then multiplied by the relative weight (p_i) of each parameter for assessing the relative impact that the uncertainty had on the vulnerability assessments carried out in this work. This exercise points out that the most significant distortions due to epistemic uncertainties are on parameters BP1, BP12 and BP2. A detailed survey campaign specifically devoted to minimising the uncertainty on these parameters would be reflected in a substantial reduction of the overall uncertainty throughout the universe of study.

Both, the Uncertainty Index and the Conservative Mean Damage Grade, constitutes feasible strategy to deal with uncertainty when having a partial availability or lack of data. The example of the National Catalogue for Historical Monuments is an example of this,

Table 10
Mean uncertainty by parameter.

Parameters	Class (C_{vi})				Weight (p_i)	Mean uncertainty (UI_p)	(UI_p)(p_i)
	A	B	C	D			
Group 1. Structural building system							
BP1. Type of resisting system	3.61%	65.06%	28.92%	2.41%	2.50	0.43	**1.07**
BP2. Quality of the resisting system	10.84%	6.02%	74.70%	8.43%	2.50	0.36	**0.90**
BP3. Conventional strength	3.61%	31.33%	61.45%	3.61%	1.00	0.32	0.32
BP4. Maximum distance between walls	28.92%	44.58%	21.69%	4.82%	0.50	0.30	0.15
BP5. Number of floors	40.96%	57.83%	0.00%	1.20%	0.50	0.30	0.15
BP6. Location and soil conditions	0.00%	100.00%	0.00%	0.00%	0.50	0.87	0.44
Group 2. Irregularities and interaction							
BP7. Aggregate position and interaction	26.51%	32.53%	10.84%	30.12%	1.50	0.22	0.33
BP8. Plan configuration	9.64%	14.46%	25.30%	50.60%	0.50	0.32	0.16
BP9. Height regularity	62.65%	22.89%	13.25%	1.20%	0.50	0.38	0.19
BP10. Wall façade openings and alignment	61.45%	2.41%	20.48%	15.66%	0.50	0.12	0.06
Group 3. Floor slabs and roofs							
BP11. Horizontal diaphragms	49.40%	25.30%	24.10%	1.20%	0.75	0.47	0.35
BP12. Roofing system	12.05%	53.01%	20.48%	14.46%	2.00	0.47	**0.93**
Group 4. Conservation status and other elements							
BP13. Fragilities and conservation status	50.60%	32.53%	16.87%	0.00%	1.00	0.38	0.38
BP14. Non-structural elements	26.51%	69.88%	2.41%	1.20%	0.75	0.22	0.17

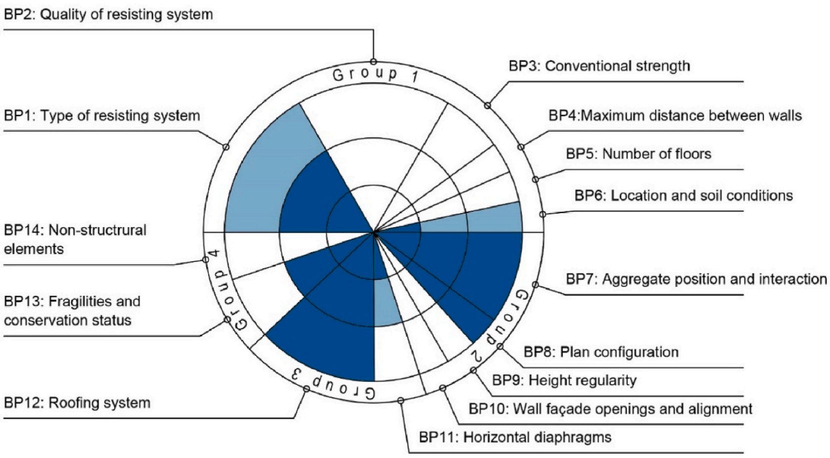


Fig. 12. Example of a graphical representation for the building SECII-27.

given that there is a vast universe of buildings that have been documented with variable levels of accuracy. Even if, in many cases, the information is not considered enough for performing detailed seismic vulnerability assessment, the information they provide is relevant and represent a valuable opportunity to complement with aspects to be enhanced.

Such vulnerability assessment involving the evaluation of a large number of parameters and enclosing information related to historical monuments in individual datasheets, clearly benefits from a graphical representation in a simplified and easy-to-use scheme that is helpful for easily communicating the vulnerability of a construction together with the level of uncertainty that its survey has at a determined moment in order to provide a more accurate description during field campaigns. Fig. 2 shown in Section 3.2 is herein revisited to exemplify the assessment for the building SECII-27. In this visual example (Fig. 12), parameters such as BP2 obtained a grade A. Thus, since grade A has a numerical value of zero, no section is shadowed in the corresponding sector. Parameter BP6 was evaluated initially with grade B, which is associated with a numerical value and consequently, the most inner circle sector or slice is colour filled (dark blue). Nevertheless, as referred previously, uncertainty regarding this grading is to be considered and the light-shadowed sectors or slices (in light blue) imply that the parameter can potentially be graded as C or D. This implies a Quality Check assessment QC = 2 or QC = 3. Furthermore, the presence of the light-shadowed sectors indicates the need for further surveying of this parameter, BP6. Given that the sizes of the sectors or slices are geometrically proportional to the grade values and relative weights, the observation of such a graphical output allows correlating that a more colour-filled figure implies a higher vulnerability index. Additionally, another useful interpretation of this graphical output is uncertainty on the assessment of some parameters, indicated by the presence of lighter coloured sectors.

6. Final remarks and future work

Seismic risk represents a relevant agent for human settlements, given the grade of destructiveness that a single event can impose. Furthermore, experiences such as the 2017 Earthquakes in Mexico demonstrate the relevance of promoting awareness through simple to more complex approaches to assess the structural and seismic vulnerability of traditional constructions to cultural assets. It is acknowledged that previous works devoted to risk prevention and assessment in the Mexican context are noteworthy; however, the large-scale assessment of historical constructions is still a gap. Nevertheless, the existence of a National Catalogue of Historical Monuments presents an interesting opportunity for performing simplified approaches, resourcing to the Vulnerability Index Method, herein presented, adapted and exposed.

The present document implemented the Vulnerability Index Method approach for assessing a total of 83 buildings/constructions in the historic city of Atlixco, Puebla. Adopting this method demanded performing a detailed analysis of all parameters for the building and façade approach to assess the necessary slight redefinition and adapting criteria. A nuclear part of this exercise has been the adjustment of the parameters in order to fit the criteria to the Mexican built environment. This process demanded more than a translation but decoding the rationale and the justification behind the criteria.

Despite the great value of the available information, the sources of data presented several gaps during the data-acquisition process. Given the difficulties for addressing them by performing on-site visits, a framework for contextualising and documenting the uncertainty was developed. This strategy is aimed to be adopted as a response to the lack of information, a common issue when reviewing existing databases. The implementation of a strategy based on assuming the uncertainty for defining plausible ranges for the vulnerability index and consequently the mean damage grades, instead of closed values resulted coherent and suitable for testing the methodology against the observed damages after the 19th of September 2017 event.

The results of the assessment exhibit a good correspondence between the forecasted mean damage grades with the real and observed damage in buildings. This qualitative correspondence suggests the suitability of using this approach for assessing masonry structures in Mexico, accepting the eventual need of adapting the criteria for vulnerability class grading (such as herein presented). The strategies herein presented for contextualising and documenting the uncertainty during data acquisition are more than an instrumental assumption. Those strategies are meant for using existing information as a starting point regardless of its accuracy or quality, not overlooking the issue and taking it into account for a more robust analysis. Even if the present state of information (namely contained in the National Catalogue of Historical Monuments) is considered insufficient for performing large-scale seismic vulnerability assessments, the information contained can be complemented with additional information that could be seen as to be included into the current updates of the datasheets of the National Catalogue. If information is scarce and potentially leading to a range of values for the seismic vulnerability indices and mean damage grade values, the definition of a qualitative comparison and other graphical analysis would facilitate the use of that information for decision-making.

The results and the ability to use this method for assessing the seismic vulnerability of masonry constructions in Mexico may be limited because of the representativeness of the buildings of Atlixco when compared to different built environments in the country. However, it is important to note that no relevant typological divergences from the typical constructions of the central region of the country were found. All the parameters of the method were suitable for assessing the constructions, supporting the adoption of this method for other environments in which the parameters (and their grading conditions) are reasonably applicable. The hypothesis of extrapolating the method to another construction environment that fits the conditions considered in Annex 1 is then sustained. Nevertheless, it is convenient to consider the relevance of testing the approach in the context of experimental data for more accurate grading and selection of ductility values. Another opportunity for enhancement lies in defining a more-suitable scale for damages, consistent with the common failures and mechanisms found in the Mexican built environment, including the adoption of continuous grade scales instead of closed discrete grades for assessing some quantitative parameters.

The ranges for real/observed damage and the forecasted/calculated mean damage grade are often overlapped, representing a good precedent for performing a series of potential future works that would improve the application of this approach. An experience with more accurate data (i.e., with a better resolution) would facilitate performing sensibility analysis for testing numerous possibilities under the basis of the results herein presented. For example, adjustments on the parameter's weights, the impact of the suppression of some parameters that present no variability among the samples or even the inclusion of new parameters, using data from the Mexican National Atlas of Risk or social vulnerability indicators for involving more stakeholders interested in the impact of seismic risk in human settlements are foreseen.

Funding

This research was funded by the Portuguese Foundation for Science and Technology (FCT) through the grant number PD/BD/150385/2019.

Availability of data and material

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been possible thanks to M. Arch. Aurelia Flores Rodríguez, Francisco Ruíz Herrera, Pedro Martínez Bret, and Eduardo Tototzintle Huitle, that generously shared the work developed in the Benemérita Universidad Autónoma de Puebla. A special acknowledgment for Dr. Carlos Montero Pantoja, that allowed to open communication channels during the COVID-19 lockdown.

ANNEX I.

Parameters and criteria for the application of the Vulnerability Index Method for masonry buildings

Type and organisation of the resisting system (BP1): This parameter assesses the type of resistant system based on the organisation of the walls, the quality of the construction fabric, the efficiency of the connections of the orthogonal walls and the eventual use of building codes for seismic design or retrofitting. The classes depend on the accomplishment of a series of properties of the walls, as summarised in Table 1. The existence of perimetral beams or straps and tie-rods is uncommon in Mexican typologies. Hence, the proposed classes for Atlixco building stock depends on the existence of an adequate project and on the quality of the bonding, interlock, and structural connections. For Atlixco, this information may be taken from the information available in fields F4, F8, F13, F14, F15, F16 and F17 of the data sheet.

Table 1
Classes for the parameter BP1.

Class	Original description [31]	Adjustments for Atlixco, Puebla
A	Built according to earthquake design codes or guidelines or, alternatively, strengthened according to codes for retrofitting and reparation that guarantee efficient connections amongst vertical elements and amongst vertical and horizontal elements.	Repaired, reinforced and/or built according to the construction codes. The project and execution had the corresponding licenses and have been approved by the INAH or other corresponding authority.
B	There is good bond and connections of orthogonal masonry walls. There is an efficient transmission of vertical and shear loads. There are perimetral beams/straps and tie-rods in all floors, with an adequate cross section and anchorage according to the thickness of the wall.	There is no evidence of the criteria of (class A), but the visual information allowed to conclude an adequate bonding and interlocking of the walls. The elements assure an efficient connection and transmission of vertical and shear loads.
C	The building does not present the connections stated for class B or present them in some floors. Nevertheless, there is a good connection among orthogonal walls due to an adequate bond and locking of masonry.	Conditions of class B are not present in at least one visible structural connection.
D	The building does not present well-connected walls. Total absence of tie-rods and straps.	Conditions of class B are not present in any visible structural connection.

Quality of the resisting system (BP2): This parameter assesses the quality of masonry based on three aspects (see Table 2):

a) Homogeneity, shape, size, and material of the masonry units, as well as the joint mortar composition.
b) Configuration and bonding of the masonry fabric. It becomes relevant to recognise if there are well-defined and apparent vertical and horizontal joints or if there is an irregular stone laying that leads to an irregular mortar joint distribution. The presence of brick our stone courses, constituted by units with the total width of the wall) or the existence of relatively large units of stone next to wall openings or corner angles does not denote a lack of homogeneity.
c) Presence of transversal connection elements with the width of the wall, in cases of two leaves wall (common in the case if stone masonry.

The Mexican catalogue is much less explicit when describing the material nature or source of the walls, giving some short material descriptions that do not provide information about the bonding or joints (Field F4). Furthermore, there is a relevant semantical divergence since the materials are not selected from a closed set but are declared as a text chain in which every cataloguer is able to introduce very specific terms. The criteria for Atlixco derived from the association of the descriptions found in the Catalogue and those taken from Ref. [31]. The semantic descriptions found in the Catalogue are often over-generalising and may fail at representing the real materiality of the construction. Moreover, the class definition of this parameter is supported, in many cases, with pictures instead of the given description, allowing to classify accordingly.

Table 2
Classes for the parameter BP2.

Class	Original description [31]	Criteria for Atlixco
A	(A1) Stone masonry with homogeneous units in size and material, well carved or cut (parallelepipeds), good bonding and good quality mortar, with vertical and horizontal joints; (A2) Low porosity stone masonry with good bonding and interlocking and good vertical and horizontal joints. Good quality mortar. (A3) Masonry with perforated units (<45% of voids) with good vertical and horizontal joints and good quality mortar. (A4) Stone masonry with structure of timber (*gaiola pombalina*), with a good state of conservation, efficient connections between the elements of timber and no signs of decay by biologic attack or moisture decay. (A5) Solid brick masonry or solid blocks with good layering and interlocking; vertical and horizontal joints with good quality mortar. (A6) Strengthened and consolidated masonry (crack injections).	- Brick or stone masonry.
B	(B1) Stone masonry with units of heterogeneous size, but well carved or cut and well bonded along the length and width of the wall. Good quality mortar. (B2) Stone masonry with uncarved or barely carved units. Transversal connection: stones or ceramic pieces across the width of the wall. Good quality mortar. (B3) Adobe masonry laid at one time, or one and a half times, with mortar of good quality. (B4) As A3, but only present horizontal joints or medium quality mortar. (B5) As A2, but with medium quality mortar. (B6) As A5, with signs of decay in timber or discontinuity of the elements.	- Brick or stone masonry and adobe.
C	(C1) Coarsely carved stone masonry, irregular in shape, with irregular locking and laying. Medium quality mortar. (C2) Stone masonry with rounded and irregular units. Transversal connection and medium quality mortar. (C3) Solid brick masonry with deficient laying and poor mortar quality. (C4) Stone masonry with irregular units. Irregular laying and low-quality mortar. (C5) Two leaves stone masonry with irregular units, heterogeneous stone fragments and a solid quality core (consolidated filling material). Irregular laying and medium quality mortar.	- Adobe, rounded stone, and clay brick. - Stone masonry and brick masonry. - Rounded stone, volcanic stone, and clay brick. - Adobe, round stone, and clay brick.

(*continued on next page*)

Table 2 (*continued*)

Class	Original description [31]	Criteria for Atlixco
D	(C6) Adobe masonry overlayed at one half of length. Medium quality mortar. (D1) Rammed earth (D2) Unworked stone masonry, with medium or high porosity. Deficient unit laying (with voids), without transversal connections. Low quality mortar. (D3) Brick masonry with units of low quality and laying with the use of unit fragments. Deficient layering and interlocking. Low quality mortar. (D4) Two leaves stone masonry with a partially empty and unstable inner core. Low quality mortar.	- Adobe.

Conventional strength (BP3). This parameter assesses the global shear strength of the building when subjected to seismic action (equivalent force approach). The base assumptions are an infinite stiffness of the diaphragms (neglecting irregularities in plan), and the strength is independently calculated in two directions. The weaker direction (i.e., that with the minor resistant section) is analysed as an equivalent shear wall (i.e., such as a masonry wall subjected to a vertical load and a horizontal force). The seismic force is considered the total weight of each storey level and the maximum shear strength in each direction. The strength of the equivalent shear wall in-plane is calculated by the means of the expression of Turnšek and Čačovič (Eq. (5)). The equivalent seismic force is calculated according to the Italian Norm D.M. 16.01.1996 (Eq. (3)).

$$\tau_u = A \times \tau_k \sqrt{1 + \left(\frac{\sigma_o}{1.5 \times \tau_k}\right)} \tag{5}$$

where.

τ_u is the ultimate shear strength (kPa);
A is the cross section of the equivalent wall (length × width); (m^2)
τ_k is the characteristic shear strength (kPa);
σ_0 is the normal vertical stress (load divided by wall cross section area).

$$F_s = 0.4 \times W \tag{6}$$

where.

W is the total vertical load on the wall.

Eq. (5) is able to be reformulated in function of the characteristic shear strength τ_k and the vertical load σ_o, (considering the permanent and quasi-permanent loads of all storeys above the level of verification), obtaining a coefficient C_{conv} (Eq. (7)) that represents the conventional shear strength of the equivalent wall in the less favourable direction, considering the difference of resisting wall area among both principal directions.

$$C_{conv} = \frac{a_0 \times \tau_k}{q \times N} \sqrt{1 + \frac{q \times N}{1.5 \times a_0 \times \tau_k \times (1+\gamma)}} \tag{7}$$

where.

N is the number of levels above the level of analysis (including it);
τ_k is a reference value of 60 kPa;
$a_0 = A_{min}/A_t$, where A_{min} is the minor of the A_x, A_y wall section directions (XX, YY) and $A_t = A_x + A_y$ in m;
$\gamma = A_{min}/A_{max}$;

q is the mean weight of a storey level by unit of covered area, including the self-weight of walls and diaphragms (Eq. (8)).

$$q = \frac{(A_x + A_y) \times h \times p_m}{A_t} + p_s \tag{8}$$

Where.

h is the mean free height of the stories in m;
p_m is the density of the masonry in kN/m^3;
p_s is the weight by area of the diaphragms in kN/m^2.

The characteristic strength of the masonry is able to be based on experimental evidence or according to local construction codes and/or recommendations, such as the Italian code D.M. July 2, 1981, GNDT-SSN. The class for this parameter is given by the ratio, $\alpha = C_{conv}/\overline{C}$ (Table 3), where the reference value for $\overline{C}$ is 0.4, correspondent to a maximum seismic force in an active seismic region:

Table 3
Classes for the parameter BP3.

Class	Original description [31]	Criteria for Atlixco
A	$\alpha \geq 1.0$	$\alpha \geq 1.0$
B	$0.6 \leq \alpha < 1.0$	$0.6 \leq \alpha < 1.0$
C	$0.4 \leq \alpha < 0.6$	$0.4 \leq \alpha < 0.6$
D	$\alpha < 0.4$	$\alpha < 0.4$

The reference values for this parameter have been reviewed in order to relate them to Mexican codes and characteristic values found in literature. The values for characteristic shear strength (τ_k), weight by area of diaphragms (p_m) and density of masonry (p_s) were set according to the following principles:

(a) Diaphragms. Values for p_m and p_s.

The weight by area of diaphragms (p_s) is composed by a dead load and a live load. The Mexican Code of Construction for Mexico City [49] includes a series of standard live loads (W_a) to be used when analysing seismic design and depend on the use of the building. Since this information is taken from the datasheet, it is possible to accurately associate this value. This value is compared to the values given in Eurocode 1 [50]), since the latter could lead to more conservative values and in this case has been adopted, as per Table 4. The weight by area of the diaphragms was based on the Basic Document of Structural Safety of the Technical code for Construction [51]), as per Table 5.

Table 4
Correspondence among the uses stated in the datasheets for Atlixco against the uses and live loads found in the Mexican Code and Eurocode 1. The value for p_m was selected as the most conservative one between both codes.

Datasheet	Mexican Code of Construction for Mexico City		Eurocode 1	
Uses	Uses	Live Load (kN/m^2)	Uses	Live Load (kN/m^2)
Domestic, Hotel	Housing units: houses, apartments, rooms, hotel rooms, hostels, barrack, jails, hospitals and similar.	1.0	EC1-Housing	1.5–2.0
Government	Offices, studies and laboratories.	1.8	EC1-Medium concentration	3.0–4.0
School	Classrooms.	1.8	EC1-Medium concentration	3.0–4.0
–	Stadiums and meeting places with no individual seats.	3.5	EC1-High concentration	6.0–7.5
Religious, Leisure	Libraries, temples, cinemas, theatres, gym, ballrooms, restaurants, playrooms and similar.	2.5	EC1-Medium concentration	3.0–4.0
Commercial, Mixed,	Commerce, factories, storing areas.	3.5 (min)	EC1-High concentration	6.0–7.5
–	Roofing with pending of less than 5%	0.7	EC1-Balconies	2.5–4.0
–	Roofing with pending of more than 5%	0.2	EC1 – Non accessible roofing	0.4
–	Cantilever above a pedestrian path.	0.7	EC1-Balconies	2.5–4.0
–	Garages and parking lots. Only for automobiles.	1.0	EC1-Public garage	5.0

Table 5
Dead load associated to the materials.

Systems according to the Basic Document of Structural Safety of the Technical code for Construction	Corresponding diaphragms found in the Catalogue of Atlixco in field F5	Dead Load (kN/m^2)
Bidirectional slab total width of less than 0.30 m	Timber beam, clay brick and *terrado*.	4.0
Concrete slab of 0.20 m	Timber beam and concrete slab	5.0
Bidirectional slab total width of less than 0.30 m	Timber beam, clay brick and *petatillo*	4.0
Concrete slab of 0.20 m [51])	Concrete slab	5.0
Bidirectional slab total width of less than 0.30 m	Timber beam and clay brick	4.0
Concrete slab of 0.20 m [51])	Concrete beam and clay brick	5.0
Catalan covering. [51])	Catalan vault	2.5
Metallic sheet with concrete slab. Total width <0.12 m	Metallic beam and metallic sheet	2

(b) Masonry walls. Values for p_s and t_k.

The characteristic values for the density and shear strength for diverse typologies of masonry may be found in the works of Vicente [31]. Despite the semantic divergences found in the datasheets for Atlixco, the descriptions have been framed in similar masonry typologies in order to provide characteristic values (Table 6).

Table 6
Characteristic values for masonry walls.

[31]	Corresponding masonry typologies found in the Catalogue of Atlixco. Field F4.	Density p_s according to [31]	Characteristic shear strength t_k According to [31]
Stone (granite)	Stone masonry.	26–27	40
Stone (poor condition)	Stone masonry and adobe.	26–27	20
Round stone masonry	Adobe, round stone and clay brick.		40
Irregular masonry of volcanic stone	Stone masonry and brick masonry.	18	20

Maximum distance between walls (BP4): This parameter describes the role that orthogonal walls have on constraining an out-of-plane failure of a façade wall. This parameter is assessed based on the comparison between the width of the façade wall and two distances between effective bond or connection to walls or floors (support conditions): h_0 (the height between storeys or storey/roof efficiently connected to the façade), and L, the largest distance between orthogonal walls efficiently connected to the façade (see Table 7).

Table 7
Classes for the parameter BP4.

Class	Original definition [31]	Criteria for Atlixco
A	$\left(\frac{h_0}{s}\right)_{máx} \leq 10;\ \left(\frac{L}{s}\right)_{máx} \leq 15$	This criterion has been adopted since the datasheets provide the necessary data in fields F13 and F4.
B	$10 < \left(\frac{h_0}{s}\right)_{máx} \leq 15;\ 15 < \left(\frac{L}{s}\right)_{máx} \leq 18$	
C	$15 < \left(\frac{h_0}{s}\right)_{máx} \leq 20;\ 18 < \left(\frac{L}{s}\right)_{máx} \leq 25$	
D	$\left(\frac{h_0}{s}\right)_{máx} > 20;\ \left(\frac{L}{s}\right)_{máx} > 25$	

Number of floors (BP5): This parameter associates an increasing vulnerability according to the number of storeys of the building, given that the number of storeys is proportional to height and that tall masonry constructions are more likely to present structural irregularities (such as out-of-plane deformations). The classification criterion is given in Table 8.

Table 8
Grading for the parameter BP5.

Class	Original description [31]	Criteria for Atlixco
A	Building with 1 storey (i.e., ground level)	This criterion has been adopted since the datasheets provide the necessary data. No buildings with more than 2 storey levels were found in Atlixco and, in fact, are very uncommon in Mexican historical centres. Information of field F7.
B	Building with 2 or 3 storeys	
C	Building with 4 or 5 storeys	
D	Building with more than 6 storeys	

Location and soil conditions (BP6): Three factors are considered and combined in this parameter: the topographic environment of the building (slope, in %), type and consistency of the soil and the presence of foundations and their eventual difference of footing levels, Δh. Due to the complexity for obtaining detailed information for every single building, the methodology accepts that it is possible to assume a reasonable hypothesis for all the buildings in a region based on the available information on the typologies and/or surveys. This parameter considers that the soil can be framed in three different types according to the criteria of the Eurocode 8: Rock (soil type A); loose and not impulsive soils (types B and C); and loose and impulsive soils (types D and E). The combinations of soil types, foundations properties and slope can be found in Table 9.

Table 9
Classes for the parameter BP6.

Class	Original description [31]				Criteria for Atlixco
	Soil type	**Foundations**	**Slope (%)**	**Δh**	The assessment of this parameter results problematic in Atlixco since the information regarding the foundations is not available. In order to keep a conservative approach, the foundations were considered as inexistent. The slope was also generalised according to the information provided by the GIS
A	A	Indifferent	$p \leq 10$	Indifferent	
	B, C	Yes (stone)	$p \leq 10$	$\Delta h = 0$	
	B, C	No	$p \leq 10$	$\Delta h = 0$	
B	A	Indifferent	$10 < p \geq 30$	Indifferent	
	B, C	Yes (stone)	$p \leq 10$	$0 < \Delta h \leq 1$	
	B, C	Yes (stone)	$10 < p \leq 30$	$\Delta h \leq 1$	
	B, C	No	$p \leq 10$	$0 < \Delta h \leq 1$	
	B, C	No	$10 < p \leq 20$	$\Delta h \leq 1$	

(continued on next page)

Table 9 (*continued*)

Class	Original description [31]				Criteria for Atlixco
C	A	Indifferent	10<p ≤ 50	Indifferent	Topographic of the city [52]. No buildings are located in sloped areas of more than 10%. The type of soil was taken from the classification of CENAPRED [8] and the Municipal Geology Map [53]. The city corresponds to a deposit of dense sands, gravel and clays, equivalent to the soil class B according to Eurocode 8 classification. Then, all the buildings were classified as B for this parameter (Soil type B, with no foundations, a slope of less than 10% and a difference Δh different to zero).
	B, C	Yes (stone)	30<p ≤ 50	$\Delta h \leq 1$	
	B, C	No	20<p ≤ 30	$\Delta h \leq 1$	
	D, E	Yes	p ≤ 50	$\Delta h \leq 1$	
	D, E	No	p ≤ 30	$\Delta h \leq 1$	
D	A	Indifferent	p > 50	Indifferent	
	B, C	Yes (stone)	p > 50	Indifferent	
	B, C	Yes (stone)	Indifferent	$\Delta h > 1$	
	B, C	No	p > 50	Indifferent	
	B, C	No	Indifferent	$\Delta h > 1$	
	D, E	Yes	p > 50	Indifferent	
	D, E	Yes	Indifferent	$\Delta h > 1$	
	D, E	No	p > 30	Indifferent	
	D, E	No	Indifferent	$\Delta h > 1$	

Aggregate position and interaction (BP7): When the building is part of an aggregate or row building construction and share load bearing walls which is common in adjacent constructions, it becomes necessary to characterise the role of this interaction on the seismic behaviour of the single building. The most favourable condition is that of a building in the middle of two adjacencies with a coincidence on the diaphragms. When the horizontal diaphragms are not at the same height, a potential pounding effect should be considered. The class criteria for this parameter can be found in Table 10.

Table 10
Classes for the parameter BP7.

Class	Original description [31]	Criteria for Atlixco
A	Middle of the block. Coincident diaphragms.	This criterion has been adopted since the datasheets provide the necessary data. Information is found in fields F11 and F13.
B	Middle of the block. Non coincident diaphragms. Isolated construction	
C	In the corner of a block. Coincident diaphragms	
D	In the corner of a block. Non coincident diaphragms In the end of a block.	

Plan configuration (BP8): The structural performance of the building is conditioned by its geometrical regularity. The eccentrical volumes are meaningful for promoting significant stiffness differences and dynamic modes among the sections of a construction. In order to assess the irregularity of a construction, two ratios are considered. These analyses are based on discriminating and understanding the plan of the building as a dominant regular figure and the eccentricities associated to this regular figure. A first ratio $\beta_1 = \frac{a}{L}$ assesses the shortest (a) and the largest (L) sides of the regular part. The ratio $\beta_2 = \frac{b}{L}$ involves the largest side of the regular part (L) and the length of the side of eccentric section perpendicular to L (b), as shown in Fig. 1 The most unfavourable classification of the two potential assessments is assigned, according to Table 11.

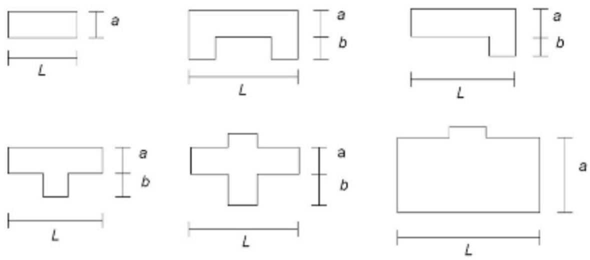


Fig. 1. Examples of L, a and b for multiple plan configurations..

Table 11
Classes for the parameter BP8.

Class	Original description [31]	Criteria for Atlixco
A	$\beta_1 \geq 0.75, \beta_2 \leq 0.1$	This criterion has been adopted since the datasheets provide the necessary data. A potential limitation, however, was found because of the frequent use of the symmetrical central patio layout. Information is found in field F12.
B	$0.5 \leq \beta_1 < 0.75, 0.1 < \beta_2 \leq 0.2$	
C	$0.25 \leq \beta_1 < 0.5, 0.2 < \beta_2 \leq 0.3$	
D	$\beta_1 < 0.25, \beta_2 > 0.3$	

Height regularity (BP9): This parameter assesses the variation of surface area between two consecutive storeys, implicitly inferring over the difference of stiffness that this variation of area can imply. The simplified approach for this assessment is through the percentual ratio $\pm\frac{\Delta M}{M}$ between the mass of two consecutive floors. Given an assumption of homogeneity of mass distribution in a building, it is possible to alternatively assume a simpler assessment based on the area ratio $\pm\frac{\Delta A}{A}$. Some modifications for this first level approach for classification are the presence of some solutions, such as a width reduction of the thickness of the walls in height, the presence of a ground floor gallery or the presence of towers. Furthermore, the contextualisation of the building in a series of constructions may imply a downgrade of the assessment just as discussed for parameter BP7. The selected grade is the worst of the applicable situations summarised in Table 12.

Table 12
Classes for the parameter BP9. The selected grade is the worst of the applicable situations.

Class	Original description [31]	Criteria for Atlixco
A	$\frac{\Delta A}{A} < 10\%$ or $\pm\frac{\Delta M}{M} < 10\%$ Building in the middle of other two with a height difference of less than ½ of a storey. Isolated construction.	This criterion has been adopted since the datasheets often provide the necessary data for classification. Nevertheless, the datasheets only consider the architectonic plan corresponding to the ground floor of the construction (field F12), limiting the assessment of ΔA. In most of cases it was possible to provide a classification based on the pictures and the visual information available in sources such as Google Maps ® and/or Google Earth ®.
B	$10\% < \frac{\Delta A}{A} < 20\%$ or $10\% < \frac{\Delta M}{M} < 20\%$ Building with a tower with a height of less than 10% of the total height of the building. Building with a gallery or arcade of less than 10% of the area of the level. Building adjacent to one or two taller constructions with a height difference of more than ½ of a storey.	
C	$20\% < \frac{\Delta A}{A} < 30\%$ or $20\% < \frac{\Delta M}{M} < 30\%$ Building adjacent to a shorter construction with a height difference of more than ½ of a storey. Building with a tower with a height between 10% and 40% of the total height of the building. Building with a gallery or arcade of between 10% and 20% of the area of the level.	
D	$\frac{\Delta A}{A} > 30\%$ or $\pm\frac{\Delta M}{M} > 30\%$ Building adjacent to two shorter constructions with a height difference of more than ½ of a storey. Building with a tower with a height of more than 40% of the total height of the building. Building with a gallery or arcade of more than 20% of the area of the level.	

Wall façade openings and alignment (BP10): The area and vertical or horizontal misalignment of openings influences the in-plane and out-of-plane failure mechanisms. The misalignment has a negative effect on the behaviour and performance of the constructions, even for vertical permanent loads, favouring concentration of stresses, which can lead to meaningful seismic cracking and instability of wall piers and spandrels. The classification criterion for this parameter is presented in Table 13.

Table 13
Classes for the parameter BP10

Class	Original description [31]	Criteria for Atlixco
A	Regular dimensions and aligned in height.	This criterion has been adopted since the datasheets often provide the necessary data for classification, namely through photographs and drawings of the façades (field F13).
B	Regular or irregular dimension horizontally misaligned in more than ½ of their height.	
C	Regular or irregular dimension vertically misaligned in more than ½ of their height.	
D	Regular or irregular dimension totally misaligned. Relatively large openings at any level of the construction	

Horizontal diaphragms (BP11): The conditions of the connections between floor diaphragms and walls as well as their ability for efficiently transmit vertical loads to the walls (and the foundations) influence the global behaviour of the buildings. The key aspects of this behaviour are the stiffness of the diaphragms and the quality of their connection to the walls. A poor connection may promote situations such as distortion, deformations, and unstable support conditions. A downgrade of the classification is considered if there is evidence of decay. The criteria for this parameter can be found in Table 14.

Table 14
Grading for the parameter BP11

Class	Original description [31]	Criteria for Atlixco
A	Rigid or semi-rigid and well connected.	The assessment of this parameter was mostly based on two sources. The first one is the description of diaphragms offered in datasheets (field F5). Every description was associated to a stiffness criterion (rigid, semi-rigid or flexible). The existence of decays was associated to the conservation state (field F8) declared in the datasheet ("good" = no decay; "regular" or "bad" = decay), supported by visual information (if available). The quality of the connections was classified according to the grade of BP1: (A, B = well connected; C, D = poorly connected).
B	Flexible and well connected. Rigid or semi-rigid and well connected, but with signs of decay*	
C	Rigid or semi-rigid and poorly connected. Flexible and well connected, but with decays*	
D	Flexible and poor connected.	
*	Weakness in the regions of contact with the vertical structure, signs of deformation, rotting or shrinkage, or lack of safety for circulation.	

Roofing system (BP12): This parameter assesses the weight, span and perimetral support conditions. The effects of the roofing system include a potential horizontal impulse onto the walls, favouring out-of-the plane failure. This parameter assesses if there is a perimetral strap or beam that contains the horizontal thrust of the roofing system, the presence of tensile elements for restraining horizontal thrusts and considers the impulsive nature and conservation state of the roofing structure (good, medium and bad). The impulsiveness of the roofing system is based on three potential situations:

a) Non impulsive roofing systems. Plane structures, trusses, and gabled roofs with tie-rods to absorb horizontal stresses.
b) Sightly impulsive roofing systems. Gabled roofs without tensors cancelling horizontal stresses and a span/height proportion $l/h < 20$.
c) Impulsive roofing systems. Gabled roofs without tie-rods cancelling horizontal stresses and a span/height proportion $l/h > 20$.

The matrix for deciding the classification of this parameter is presented in Table 15.

Table 15
Classes for the parameter BP12.

Class	Original description [31]			Criteria for Atlixco
	Impulsive nature	Perimetral straps/beam	State of conservation	This criterion has been adopted since the datasheets often provide the necessary data for classifying, namely through the description of the field F6. The state of conservation was directly taken from the field F8 of the datasheet. The existence of perimetral straps or beams of tensile-resistant elements was not observed in the case of study.
A	Non imp.	At least one of both	Good	
B	Non imp.	At least one of both	Bad	
	Non imp.	None of them	Good	
	Sightly imp.	At least one of both	Good	
C	Non imp.	At least one of both	Very bad	
	Non imp.	None of them	Bad	
	Sightly imp.	At least one of both	Bad	
	Sightly imp.	None of them	Good	
	Impulsive	At least one of both	Good	
D	Non imp.	None of them	Very bad	
	Sightly imp.	At least one of both	Very bad	
	Sightly imp	None of them	Bad or very bad	
	Impulsive	At least one of both	Bad or very bad	
	Impulsive	None of them	Indifferent	

Fragilities and conservation status (BP13): This parameter departs from the identification of evident fragilities and damages that may magnify seismic damages, precipitating some mechanisms. The most important damages to be identified are cracks, deformations and evidence of disintegration. The criterion for this parameter is summarised in Table 16.

Classes for parameter BP13.

Class	Original description [31]	Criteria for Atlixco
A	Walls in good conditions with no visible damage.	This parameter was graded by analysing the information available in fields F3, F4, F8, F14 and F15. Most of damages are mentioned in the description of the building but are also visible in the corresponding photographs. It is important to note that for all the datasheets that were surveyed after the 2017 earthquake, it was necessary to consult pre-event photographs, namely those found in the Google Maps ® database. The descriptions on the datasheets explicitly differentiate the damages occurred due to the 2017 earthquake.
B	Small and non-generalised cracks (<0.5 mm width). Signs of decay due to humidity in masonry and timber elements. Cracks in coatings that do not penetrate the support.	
C	Generalised cracks (2–3 mm width). Regular state of conservation of the walls. Serious deformations in the staircases and floor diaphragms; diagonal cracks in internal walls and cracks in the middle of openings.	
D	Walls with serious decay and cracking, even if it is not generalised. Decays that evidence a loss of strength. Cracks in sensitive locations, such as corners (e.g., due to disconnection between walls). Damages in the interfaces between roofs and walls, displacement of floor diaphragms. Rotting and decay of timber beams. Out-of-plane deformations of the walls.	

Non-structural elements (BP14): This parameter assesses the effect that certain elements impose for inducing damages in the structure. Elements such as cornices, parapets, balconies, or other external elements that are connected to the structure and promote load eccentricities on the façade walls. The assessment criterion is based on the mass of the elements and connections, as presented in. Table 17.

Table 17
Grading for the parameter BP14

	Original description [31]	Criteria for Atlixco
A	Building with no cornices, parapets or suspended elements.	This parameter is able to be classified based on the images of field F13.
B	Presence of well-connected cornices, light and small chimneys. Balconies integrated to the floor structure or walls.	
C	Presence of small external elements with a poor connection to the structure. Coatings and/or finishing generalised and well attached or localised and poorly attached.	
D	Elements of considerable weight (chimneys, water reservoirs on the rooftop, mechanical equipment attached to the walls) poorly connected to the structure. Balconies with poor connection to horizontal elements, namely those that were added to the original building. Large and poorly connected false plafond.	

Parameters and criteria for the application of the Vulnerability Index Method for masonry façade walls

FP1. Geometry of façade. This parameter assesses the ratio of the base length (B) and height (H) of the façade. The thresholds are those of Table 18.

Table 18
Grading for the parameter FP1.

	Description [31]	Adjustments for Atlixco, Puebla
A	$\frac{H}{B} < 0.40$	This parameter is able to be graded based on the images of the field F13.
B	$0.40 \leq \frac{H}{B} < 0.60$	
C	$0.60 \leq \frac{H}{B} < 1.00$	
D	$\frac{H}{R} > 1.00$	

FP2. Maximum slenderness. Slender walls are more likely to have an out-of-plane failure. Thresholds for grading the presented in Table 19, considering the quotient of the height (H) divided by the width of the wall (S).

Table 19
Grading for the parameter FP2.

	Description [31]	Adjustments for Atlixco, Puebla
A	$\frac{H}{S} \leq 9$	This parameter is able to be graded based on the images of the field F13 and the thickness reported in F4.
B	$9 \leq \frac{H}{S} \leq 15$	
C	$15 < \frac{H}{S} \leq 20$	
D	$\frac{H}{S} > 20$	

FP3. Area of openings. The response of a masonry wall panel is influenced by the configuration and dimension of openings since they determine the on-plane failure mechanisms. This parameter is easily assessed by the ratio between wall and opening areas, as expressed in Table 20.

Table 20
Grading for the parameter FP3.

	Description [31]	Adjustments for Atlixco, Puebla
A	Area of openings of less than 20%	This parameter is able to be graded based on the images of the field F13.
B	Area of openings of less than 35%	
C	Area of openings of less than 60%	
D	Area of openings of more than 60%	

FP4. Misalignment of openings. The logic that supports this parameter is comparable to BP10. Consequently, the criteria are similar, as summarised in Table 21.

Table 21
Grading for the parameter FP4.

	Description [31]	Criteria for Atlixco
A	Regular dimensions and aligned in height.	This parameter is able to be graded based on the images of the field F13.
B	Regular or irregular dimension horizontally misaligned in more than ½ of their height.	
C	Regular or irregular dimension vertically misaligned in more than ½ of their height.	
D	Regular or irregular dimension totally misaligned. Relatively large openings at any level of the construction	

FP5. Interaction between continuous façades. This parameter was not considered in the proposal of Vicente [31], but has been included in the calibration of Ferreira [33] and was then adapted by Aguado [24]. The grades corresponding to this parameter assess

the potential pounding effect of contiguous constructions, similarly to the parameter BP7. The criterion for grading is explained in Table 22.

Table 22
Grading for the parameter FP5.

	Description [24]	Criteria for Atlixco
A	In the middle of two façades of the same height.	This parameter is able to be graded based on the images of the field F13 and the localisation plan of F11. A limitation found for this parameter is the attachment to only one taller façade.
B	Contiguous to a façade of the same height and a shorter one.	
C	Contiguous to two shorter façades.	
D	Contiguous to only one, shorter façade.	

FP6. Quality of materials. This parameter corresponds to parameter BP2. Therefore, the grading criteria is the same. A similar situation occurs with the parameter FP7, State of conservation, that has direct correspondence to parameter BP13.

FP8. Replacement of the original flooring system. This parameter was also introduced in the calibrations of Aguado and Ferreira [24,33]. Describes the proportion of horizontal diaphragms that were replaced by reinforced concrete structures (in percentage P), accepting that this replacement is a source of damage for masonry walls. The grades considered by Aguado are summarised in Table 23.

Table 23
Grading for the parameter FP8.

	Description [24]	Criteria for Atlixco
A	$0 \leq P < 25\%$	Even if there is no quantitative information for grading this parameter, the descriptions found in fields F5, F6, F14 and F16 supported a guess for assigning a class.
B	$25 \leq P < 50\%$	
C	$50 \leq P < 75\%$	
D	$75 \leq P < 100\%$	

FP9. Connection to orthogonal walls. An efficient connection between the façade and the perpendicular walls minimises the out-of-plane mechanisms. The assessment criteria for this parameter are summarised in Table 24.

Table 24
Grading for the parameter FP9.

	Description [24]	Criteria for Atlixco
A	The façade is well connected to the orthogonal walls, diaphragms, and roofing structures by the means of metallic perimetral straps, tie rods and well locked masonry. These connections exist in all orthogonal connections.	The assessment of this parameter is based on BP11.
B	Masonry well locked in the corners, with no signs of fragility. Conditions of grade A exist in some corners.	
C	There is no good connection between the façade and the orthogonal walls. However, there are no signs of fragility. Conditions of grade B exist in some corners.	
D	The façade is deformed with an elevated risk of imminent failure (cracked according to mechanism patterns). Detachments and cracking in corners and orthogonal interfaces.	

FP10. This parameter is similar to FP9 but addressed to the connections between the façade wall and the diaphragms and roofing structures. While parameter FP9 considers a qualitative grading, FP10 gives a grade based on the proportion of efficient connections (in percentage *e*). This parameter complements parameters BP11 and BP12, involving the decays considered for BP11. The grading is given as explained in Table 25.

Table 25
Grading for the parameter FP10.

	Description [31]	Criteria for Atlixco
A	$e \geq 75\%$	Even if there is no quantitative information for grading this parameter, the descriptions found in fields F5, F6, F14 and F16 supported a guess for assigning a class.
B	$e \geq 75\%$, with decays* $50\% \leq e < 75\%$	
C	$50\% \leq e < 75\%$ with decays* $25\% \leq e < 50\%$	
D	$25\% \leq e < 50\%$ with decays* $e < 25\%$	
*	Weakness on the regions of contact with the vertical structure, signs of deformation, rotting or shrinkage, or lack of safety for circulation.	

FP11. Impulsive nature of roofing system. This parameter is equivalent to BP12. Therefore, the grading criteria is the same.

FP12. Elements connected to the façade. This parameter is similar to BP14, but the criterion for grading is slightly different since it only involves elements of the façade. The most common situations of attached elements that may condition the overturning of the façade is summarised in Table 26.

Table 26
Grading for the parameter FP12.

	Description [31]	Criteria for Atlixco
A	There are no elements attached to the façade.	This parameter is able to be graded based on the images of the field F13.
B	Some light elements, such as lights, signals, light roofs, etc.	
C	Medium weight elements attached to the façade: equipment, air-conditioned devices, etc.	
D	Existence of balconies or other heavy elements connected to the façade.	

FP13. Improving elements. This parameter was added in the calibrations of Aguado and Ferreira [24,33], recognising the role that some elements in contact to the external side of the façade have for mitigating out-of-plane failures, regardless of their explicit structural function. Some common elements are mentioned in Table 27.

Table 27
Grading for the parameter FP13.

	Description [24]	Criteria for Atlixco
A	There are no external elements.	This parameter is able to be graded based on the images of the field F13.
B	Presence of exterior stairs, arches, giants, etc.	
C	Explicit reinforcement through the use of reinforced plasters.	
D	Strengthening actions by the means of elements such as buttresses or similar.	

References

[1] United Nations Office for Disaster Risk Reduction, Economic Losses, Poverty and DISASTERS 1998-2017, 2018.
[2] UNISDR - United Nations Office for Disaster Risk Reduction, GAR Atlas: Unveiling Global Disaster Risk, first ed., Imprimerie Gonnet, Geneva, 2017.
[3] S. Caprano, S. Ortiz, R. Valencia, Los efectos económicos de los sismos de septiembre, Rev Econ Inf 408 (2018) 16–33.
[4] Coordinación Nacional de Monumentos Históricos Catálogo Nacional de Monumentos Históricos Inmuebles. https://www.catalogonacionalmhi.inah.gob.mx/. (Accessed 27 October 2020).
[5] S. Lindero, Restaurar Monumentos Históricos Costará 12 Mil Mdp: INAH. El Her, México, 2017.
[6] Secretaria de Cultura, Sismos Y Patrimonio Cultural, first ed., Secretaría de Cultura, Mexico, 2018.
[7] International Organization for Standardization, ISO 31000 Risk Management — Principles and Guidelines, 2006, 61010-1 © Iec2001 2006:13.
[8] Centro Nacional de Prevención de Desastres, Evaluación de la Vulnerabilidad Física y Social, first ed., CENAPRED, Mexico, 2006.
[9] Y.Y. Haimes, On the complex definition of risk: a systems-based approach, Risk Anal. 29 (2009) 1647–1654, https://doi.org/10.1111/j.1539-6924.2009.01310.x.
[10] N. Brooks, Vulnerability, Risk and Adaptation: A Conceptual Framework, 2003.
[11] F De Luca, G.M. Verderame, Encyclopedia of Earthquake Engineering, 2014.
[12] C. Gavarini, Seismic risk in historical centers, Soil Dynam. Earthq. Eng. 21 (2001) 459–466, https://doi.org/10.1016/S0267-7261(01)00027-6.
[13] R.S. Vicente, J.A.R. Mendes da Silva, H. Varum, Seismic vulnerability assessment of buildings in the old city centre of Coimbra, in: Proceedings of the International Conference 250th Anniversary of the 1755 Lisbon Earthquake. Lisbon, 2005, pp. 1–4.
[14] C.S. Oliveira, Seismic vulnerability of historical constructions: a contribution, Bull. Earthq. Eng. 1 (2003) 37–82, https://doi.org/10.1023/A:1024805410454.
[15] G. Cocco, A. D'Aloisio, E. Spacone, G. Brando, Seismic vulnerability of buildings in historic centers: from the "urban" to the "aggregate" scale, Front. Built Environ. 5 (2019), https://doi.org/10.3389/fbuil.2019.00078.
[16] M.R. Valluzzi, On the vulnerability of historical masonry structures: analysis and mitigation, Mater. Struct. Constr. 40 (2007) 723–743, https://doi.org/10.1617/s11527-006-9188-7.
[17] D. Gautam, R. Adhikari, R. Rupakhety, P. Koirala, An empirical method for seismic vulnerability assessment of Nepali school buildings, Bull. Earthq. Eng. 18 (2020) 5965–5982, https://doi.org/10.1007/s10518-020-00922-z.
[18] H. Azizi-Bondarabadi, N. Mendes, P.B. Lourenço, N.H. Sadeghi, Empirical Seismic Vulnerability Analysis for Masonry Buildings Based on School Buildings Survey in Iran, 2016.
[19] D. Benedetti, V. Petrini, Sulla vulnerabilita sismica di edifici in muratura: proposta su un metodo di valutazione. A method for evaluating the seismic vulnerability of masonry buildings, L'industria delle Costr (1984) 66–74.
[20] GNDT-SSN, Scheda di Esposizione e Vulnerabilità e di Rilevamento Danni di Primo e Secondo Livello (Murata e Cemento Armato), 1994 (Rome, Italy).
[21] P. Roca, M. Cervera, G. Gariup, L. Pela', Structural analysis of masonry historical constructions. Classical and advanced approaches, Arch. Comput. Methods Eng. 17 (2010) 299–325, https://doi.org/10.1007/s11831-010-9046-1.
[22] G.M. Calvi, R. Pinho, G. Magenes, et al., Development of seismic vulnerability assessment methodologies over the past 30 years, ISET J. Earthq. Technol. 43 (2006) 75–104.
[23] T.M. Ferreira, R. Maio, R. Vicente, Seismic vulnerability assessment of the old city centre of Horta, Azores: calibration and application of a seismic vulnerability index method, Bull. Earthq. Eng. 15 (2017) 2879–2899, https://doi.org/10.1007/s10518-016-0071-9.
[24] J.L.P. Aguado, Vulnerability Assessment as a Tool to Mitigate and Manage Seismic Risk in Old Urban Areas, University of Minho, 2017.
[25] T.M. Ferreira, R. Vicente, J.A.R. Mendes da Silva, et al., Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal, Bull. Earthq. Eng. 11 (2013) 1753–1773, https://doi.org/10.1007/s10518-013-9447-2.
[26] A. Blyth, B. Di Napoli, F. Parisse, et al., Assessment and mitigation of seismic risk at the urban scale: an application to the historic city center of Leiria, Portugal, Bull. Earthq. Eng. 18 (2020) 2607–2634, https://doi.org/10.1007/s10518-020-00795-2.
[27] A.E. Athmani, A. Gouasmia, T.M. Ferreira, et al., Seismic vulnerability assessment of historical masonry buildings located in Annaba city (Algeria) using non ad-hoc data survey, Bull. Earthq. Eng. 13 (2015), https://doi.org/10.1007/s10518-014-9717-7.
[28] M. Mosoarca, I. Onescu, E. Onescu, et al., Seismic vulnerability assessment for the historical areas of the Timisoara city, Romania, Eng. Fail. Anal. 101 (2019) 86–112, https://doi.org/10.1016/j.engfailanal.2019.03.013.
[29] M. Hadzima-Nyarko, G. Pavić, M. Lešić, Seismic vulnerability of old confined masonry buildings in Osijek, Croatia, Earthq. Struct. 11 (2016) 629–648, https://doi.org/10.12989/eas.2016.11.4.629.
[30] F. Giuliani, Seismic Risk Management in Historic Centres Integrated Large-Scale Modelling for a Scenario-Based Methodology, University of Pisa, Pisa, Italy, 2020.

[31] R. Vicente, Estratégias e metodologias para intervenções de reabilitação urbana. Avaliação da vulnerabilidade e do risco sísmico do edificado da Baixa de Coimbra, Universidade de Aveiro, 2008.
[32] T.M. Ferreira, R. Vicentea, H. Varum, Seismic vulnerability assessment of masonry facade walls: development, application and validation of a new scoring method, Struct. Eng. Mech. 50 (2014) 541–561, https://doi.org/10.12989/sem.2014.50.4.541.
[33] T.M. Ferreira, R. Maio, A.A. Costa, R. Vicente, Seismic vulnerability assessment of stone masonry façade walls: calibration using fragility-based results and observed damage, Soil Dynam. Earthq. Eng. 103 (2017) 21–37, https://doi.org/10.1016/j.soildyn.2017.09.006.
[34] J.L.P. Aguado, T.M. Ferreira, P.B. Lourenço, The use of a large-scale seismic vulnerability assessment approach for masonry façade walls as an effective tool for evaluating, managing and mitigating seismic risk in historical centers, Int. J. Archit. Herit. 12 (2018) 1259–1275, https://doi.org/10.1080/15583058.2018.1503366.
[35] L.G.F. Salazar, T.M. Ferreira, Seismic vulnerability assessment of historic constructions in the downtown of Mexico City, Sustainability 12 (2020) 1–21, https://doi.org/10.3390/su12031276.
[36] J. Ortega, G. Vasconcelos, H. Rodrigues, M. Correia, A vulnerability index formulation for the seismic vulnerability assessment of vernacular architecture, Eng. Struct. 197 (2019) 109381, https://doi.org/10.1016/j.engstruct.2019.109381.
[37] Congreso de los Estados Unidos Mexicanos, Ley Federal sobre Monumentos y Zonas Arqueológicos, Artísticos e Históricos. Diario Oficial de la Federación, México, 1986.
[38] R. Ramírez Eudave, T.M. Ferreira, On the potential of using the Mexican National Catalogue of Historical Monuments for assessing the seismic vulnerability of existing buildings: a proof-of-concept study, Bull. Earthq. Eng. (2021), https://doi.org/10.1007/s10518-021-01154-5.
[39] P. Martínez Bret, Catálogo de zona de monumentos, Atlixco, Puebla, sector 1. Un enfoque contemporáneo de catalogación del patrimonio cultural, Benemérita Universidad Autónoma de Puebla, 2018.
[40] F. Ruíz Herrera, Catálogo de zona de monumentos, Atlixco, Puebla, sector 3. Un enfoque contemporáneo de catalogación del patrimonio cultural, Benemérita Universidad Autónoma de Puebla, 2018.
[41] E. Tototzintle Huitle, Catálogo de zona de monumentos, Atlixco, Puebla, sector 4. Un enfoque contemporáneo de catalogación del patrimonio cultural, Benemérita Universidad Autónoma de Puebla, 2018.
[42] A. Flores Rodríguez, Catálogo de zona de monumentos, Atlixco, Puebla, sector 2. Un enfoque contemporáneo de catalogación del patrimonio cultural, Benemérita Universidad Autónoma de Puebla, 2019.
[43] G. Grünthal, L'Échelle Macrosismique Européenne (EMS-98), Joseph Beffort, Helfent-Bertrange, Luxembourg, 1998.
[44] F. Bramerini, G. Di Pasquale, G. Orsini, et al., Rischio sismico del territorio italiano. Proposta di una metodologia e resultati preliminari, 1995. Rapporto tecnico SSN. RT/95/1. Roma.
[45] S. Lagomarsino, S. Giovinazzi, Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings, Bull. Earthq. Eng. 4 (2006) 415–443, https://doi.org/10.1007/s10518-006-9024-z.
[46] USGS, M 7.1 - 1km E of Ayutla, Mexico, interactive map, in: Earthq. Hazards Progr, 2017. https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20/map?historic-seismicity=true&shakemap-intensity=false. (Accessed 22 January 2021).
[47] R.M.W. Musson, G. Grünthal, M. Stucchi, The comparison of macroseismic intensity scales, J. Seismol. 14 (2010) 413–428, https://doi.org/10.1007/s10950-009-9172-0.
[48] Administración Pública de la Ciudad de México, Acuerdo por el que se actualizan las Normas Técnicas Complementarias para diseño por sismo con comentarios, Gac. Of. la Ciudad México (2020).
[[49] Gobierno del Distrito Federal, Reglamento de Construcciones para el Distrito Federal, first ed., Gaceta Oficial de la Ciudad de México, México, 2017.
[50] European Comitee for Standardization, EN 1991-1-1 (2002) (English): Eurocode 1: Actions on Structures - Part 1-1: General Actions - Densities, Self-Weight, Imposed Loads for Buildings, first ed., European Comitee for Standardization, Brussels, 2002.
[51] Ministerio de Fomento, Documento básico SE-AE Seguridad Estructural. Acciones en la Edificación, Codigo Técnico la Edif (2009) 1–42.
[52] INEGI - Instituto Nacional de Estadística y Geografía, Conjunto de datos vectoriales de información topográfica E14B52 (Atlixco) escala 1:50 000 serie III. Pue, in: Datos Abiertos - Gob. México, 2019.
[53] A de Atlixco, Planes Municipales de Desarrollo, 2014.