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SEISMIC VULNERABILITY AND RISK ASSESSMENT FOR METRO-POLITAN AREAS OF SAN SALVADOR - THE CASE STUDY SANTA TECLA

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Abstract

The republic of El Salvador is struck by a destructive earthquake, or earthquake sequence, once per decade on average. With a geographical extension of a little more than 20,000 km2, the frequency of damaging earthquakes clearly demonstrates that El Salvador is a country of very high seismic hazard. Indeed, the capital city, San Salvador, is probably the city in the Americas that has been most frequently damaged by earthquakes. The city and municipality of Santa Tecla is the capital of the La Libertad department and belongs to the Metropolitan Area of San Salvador (AMSS). The city was founded on 1854 with main goal to be the new capital of El Salvador after San Salvador was completely destroyed by an Earthquake, objective which did not materialized after all. Nevertheless, Santa Tecla has experienced the same fate of its neighbor, being greatly damaged by the 2001 earthquakes where, at least, 80% of its historical center was destroyed. Santa Tecla has been identified as one of the most critical areas in the AMSS in terms of seismic risk due to both its geological settings and construction practices. Therefore, the urban area of Santa Tecla was selected to conduct a research. This was the first study of this type performed in an urban area in El Salvador which included exposed elements belonging to the housing, business and industry portfolios. Structures in those portfolios has been surveyed and categorized into typologies. Vulnerability classes have been assigned following the EMS-98 principles, where applicable. This process has given a unique insight about the structural systems commonly found in El Salvador. In addition, the applicability of EMS Vulnerability Table and the need of refinements to cover the variety existing building types could be elaborated.

Keywords: EMS-98, Vulnerability, Seismic Risk, El Salvador.

1. Introduction

El Salvador is located in an active seismic region produced by the subduction of the Cocos plate under the Caribbean Plate; as a consequence of this interaction, there is local seismicity, within the country, as well as active volcanoes. Consequently, El Salvador has earthquakes with sources both in the subduction zone and in the interior of the Caribbean Plate, at the so called local geological faults. San Salvador city is probably the most damage capital in the Americas due to earthquakes [1]. In the last 100 year losses due to seismic activity has reached USD 3,406,500,000 and 2,549,991 people have been affected, accounting for more than the 50% of total losses from disasters produced by natural hazards [2].

Recent seismic events (October 1986, Mw 5.7; January 2001, Mw 7.7 and February 2001, Mw 6.6) have demonstrated how vulnerable the structures in San Salvador are. The fast and disorganized urbanization process of the city has produced negative consequences in the past and if the trend continues the risk produced by earthquakes will grow exponentially and future seismic events may produce high economic and human losses [3]. The earthquakes produced by local faults have produced the highest losses in terms of human lives, most of which had their foci close to the Metropolitan Area of San Salvador (AMSS, by its acronym in Spanish) where there is high concentration of population.

The hazard can become risk where there are structures and systems exposed to the ground shaking, and the risk level depends not only on the intensity of the movement but also to the capacity of the exposed structures to withstand the shaking. Cities located in seismic areas, such as the Metropolitan Area of San Salvador, where the levels of seismic hazard and exposure are high, the seismic risk is controlled by the vulnerability of the existent structures.

2. Area of Study

El Salvador is the smallest and the densest populated country in Central America; with an area equal to 21,040.79 km^2 and an approximate population of 6.227 million of inhabitants, the population density reaches, in average, 296 inhabitant/ km^2.

San Salvador is the capital of El Salvador. The Metropolitan Area of San Salvador is composed by 14 municipalities which are: (1) Apopa, (2) Ayutuxtepeque, (3) Cuscatancingo, (4) Ciudad Delgado, (5) Ilopango, (6) Mejicanos, (7) Nejapa, (8) San Marcos, (9) San Martín, (10) Tonacatepeque, (11) San Salvador (12) Soyapango, (13) Antiguo Cuscatlán and (14) Santa Tecla, Fig. 1. The AMSS is the neurological center of the country in terms of political, financial, economic and cultural aspects, concentrating 27% of its population and 70% of both public and private inversion in an area equal to 3% of the total territory of El Salvador.

The city and municipality of Santa Tecla (as known as Nueva San Salvador), is the capital of the La Libertad department, Fig. 2. The city was founded on 1854 with main goal to be the new capital of El Salvador after San Salvador was completely destroyed by an Earthquake, objective which did not materialized after all. Nevertheless, Santa Tecla has experienced the same fate of its neighbors, being greatly damaged by the 2001 earthquakes where, at least, 80% of its historical center was destroyed, effect which has been attributed to the local condition of the soil in the city. Santa Tecla has been identified [3] as one of the most critical areas in the AMSS in terms of seismic risk. Therefore, the urban area of Santa Tecla has been selected to conduct the present research.

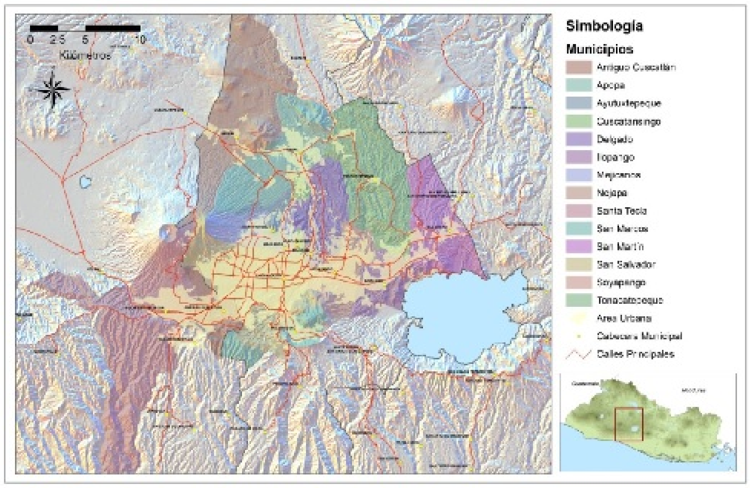


Fig. 1 - Metropolitan Area of San Salvador (AMSS)

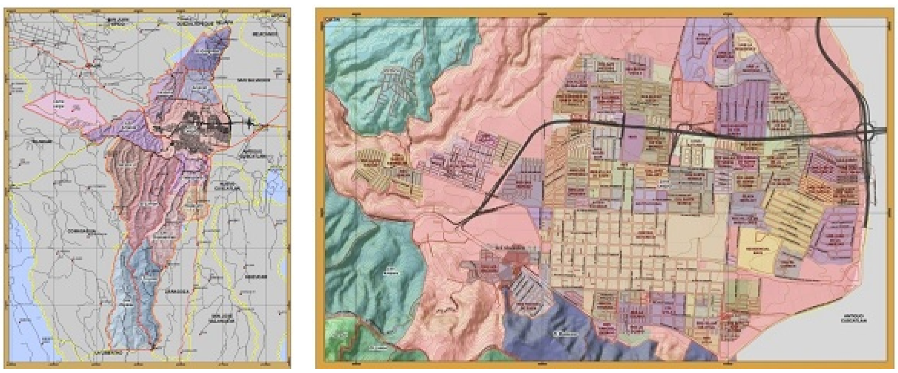


Fig. 2 - Municipality of Santa Tecla and its urban area

Table 1 - General characteristics of the area of interest

Item	Amount	Unit
Area	112,20	km^2
Population	121,908	inh
Population density	1,087	inh/km^2
Urban population	108,840 (89.3%)	inh
Rural population	13,068 (10.7%)	inh
Dwellings being inhabit	35,982	--

3. Methodology

Initial activities were related to compile and classify different sources of information such as preceding research papers and georeferenced maps of the area. Some of the available data was:

- Probabilistic modelling of seismic risk scenarios for the Metropolitan Area of San Salvador, including education, health and government portfolio analysis, in Spanish, [3].
- Consultancy services to survey information about exposed building to seismic risk, in Spanish, [4].
- Seismic vulnerability curve computation, final report; in Spanish, [5].
- Georeferenced digital maps from Viceministerio de Vivienda y Desarrollo Urbano (VMVDU), Oficina de Planificación del Área Metropolitana de San Salvador (OPAMSS) y Universidad de El Salvador (UES).

Unlike other countries, El Salvador does not possess an organize database where important information about physical and structural qualities of buildings is recorded; therefore, a field work was develop to gather this data. During surveying campaign the following information was collected using a survey sheet and the data was input to a georeferenced database.

- General Information: Location, using GPS; cadastral id; area, in m^2; portfolio (Education, Health, Government, Business, Industry and Residential); year of construction and usage.
- Technical information: Structural system; plan shape; dimensions; number of storeys; storey height; type and material of the roof; type and material of floors.
- Structural errors: Short columns, plan irregularity, elevation irregularity, weak storey, strong beam-weak column, big openings on structural walls and low quality of materials.
- Damages due to earthquakes: Date of earthquakes, 1986 or 2001; level of damage and whether damages have been repaired or not.

Although some of this information was available from a previous survey [3] for three portfolios (education, health and government), due to the characteristics of the selected area (structures belonging to residential and business portfolios) a lot of that data was not useful.

The study area was divided into seven segments, Fig. 3, to easily collect and review the field information; therefore, seven groups of people were constituted each of which was organized by two students of the Master of Structural Engineering program of the Universidad de El Salvador plus two undergraduate students belonging to the Civil Engineering career of the same University. There was an eighth group, formed by two graduated students, in charge of computing the statistics of the information. Approximately 30 people were involved into the survey campaign and all of this structure was supervised by the writer of the present report.

The study area had an extension of 5,123,371 m^2 and was set up based on the requirements expressed by the Municipality of Santa Tecla. Taking into consideration the importance of the exposed elements, location and population density, as well as number of survey takers, two distinct methods were used to collect data; the structures located at the three segments belonging to the "Centro Histórico" were surveyed one by one whilst for the ones situated at the other four segments some representative structures were sampled and their characteristics were replicated over the urban block where they belong, procedure named from here and on as the homogeneous block method.

Fig. 3 - Study area divided into the seven survey segments, three for the "Centro Histórico" and four for the outskirts.

On the vulnerability side, from previous studies [3, 5], buildings, belonging to education, health and government portfolios, were categorized into structures typologies following the classification presented on the Vulnerability Table [6] where applicable, and vulnerability curves were developed for each typology by using various methods. In the present research, the above mentioned curves were evaluated and modified if needed, in addition, new typologies, which are not presented in [3] were included and their vulnerability curves were developed such as those belonging to the residential portfolio. To accomplish the above tasks an extensive literature review was carried out, especially for the masonry case, and some of the papers are presented in the section References.

The work path to achieve the goals for the vulnerability module was the following:

- Assessment of previous vulnerability functions.
- Adjustment of previous vulnerability functions and development of new curves.
- Classification of the structural typologies depending on the information surveyed on field.
- Allocation of the vulnerability functions with the found typologies.

The methodology that was employed to develop the curves is the one proposed by [7, 8, 9, 10] where, in summary, the multi degree of freedom system is reduced to a single degree of freedom system but, unlike the HAZUS, the system behavior is controlled by the interstorey drift instead of the roof displacement of the SDOF system. The capacity curve of the SDOF system needs to be computed and, as an important characteristic of the method the percentage of damage needs to be knows for the yielding and ultimate stages. In general, the percentage of damage is around 90% to 100% for the ultimate point; however, a more meticulous approach has to be employed to find out the damage at yielding. The steps to perform this process are presented in Fig. 4.

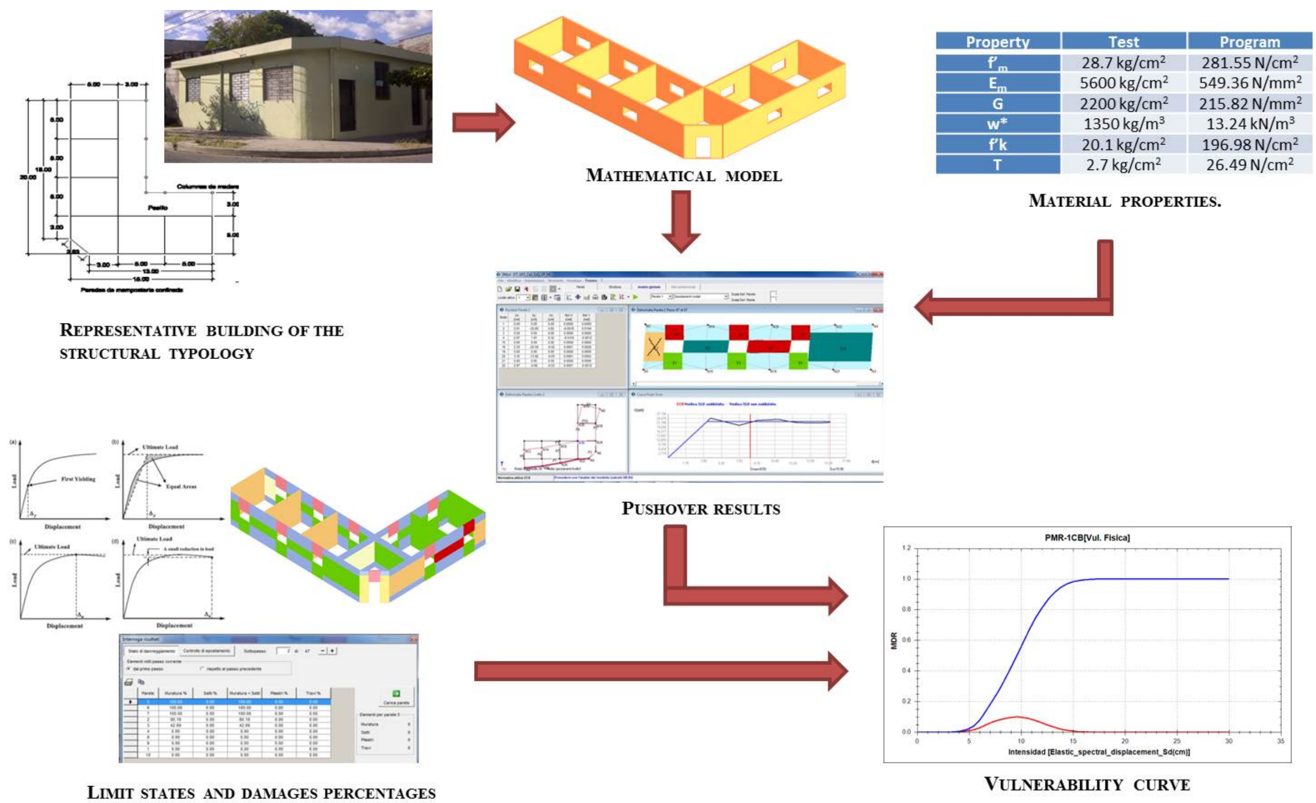


Fig. 4 - Schematic procedure of vulnerability curve development. In this methodology, the vulnerability curve is composed by two plots, the one representing the relationship between some value of intensity and the Mean Damage Ratio (blue) and another indicating the Density of the Probability of the Losses (red).

This process can be summarized as follows:

- A typical configuration is selected for each structural typology
- In order to compute the pushover and capacity curves of the structures a nonlinear analysis program is used. In the example below, TREMURI [11], is used to study masonry structures.
- The model is subjected to diverse pushover analysis changing both the shape of the force vector as well as the direction of the application of forces; the analysis which produces the lowest strength value is selected to get the vulnerability curve of the model.
- Based on the above information, meaning the capacity curves, equivalent height and period of the SDOF system, the seismic coefficient which the structure was originally designed as well as the damage states related to the analysis the vulnerability curve for each typology can be developed, in Sa (gal) vs Mean Damage Ratio (MDR) format.

4. Results

First of all, many more typologies than the ones stated in [6], or even in [3], were detected in the study area, Table 2, some of which are vernacular construction types that, nevertheless, are still used by the population in El Salvador, not only in Santa Tecla but also in most of the cities around the country. This fact suggests a need for updating the Vulnerability Table whether its goal is to make it truly globally applicable. In addition, some differentiation about the level of Earthquake-resistant Design, for typologies other than RC, is also needed.

Table 2 - Structural typologies in Santa Tecla.

EMS VC TABLE	**TYPOLOGY USED IN THIS WORK**	**ACRONYM USED IN THIS WORK**
Typology contained in EMS-98		
Adobe	Adobe	A
RC frames with moderate level of ERD	RC Moment resisting frame with seismic gap	MCCJ
RC frames without ERD	RC Moment resisting frame without seismic gap	MCSJ
Walls with moderate level of ERD	RC Structural walls	PCR
Reinforced or confined masonry	Reinforced Masonry walls (including Confined masonry walls)	PMR
Steel structures	Unbraced Steel frames	MASA
Steel structures	Braced steel frames	MACA
Unreinforced masonry, with manufactured stone units	Unreinforced masonry walls	PMSR
Timber structures	Wood	M
Typology absent in EMS-98		
	Bahareque	B
	Light steel structure	PO
	Precast structures	PR
	Precarious structure	SP

Note: Each typology has been subdivided by height (three subcategories) and by seismic code (three subcategories); 48 typologies were developed in total.

As mentioned above, the exposed elements in the "Centro Histórico" were surveyed by three groups. 1928 structures were found in this area, and their locations are illustrated in Fig. 5.

Most of the constructions in this area belong to the portfolio "Housing" with little less than 2/3 of the surveyed structures falling into this category, Fig. 6; however, there is an important percentage of structures used as business, fact which can be explained because this is the downtown area of Santa Tecla where the economic activity of the municipality is concentrated.

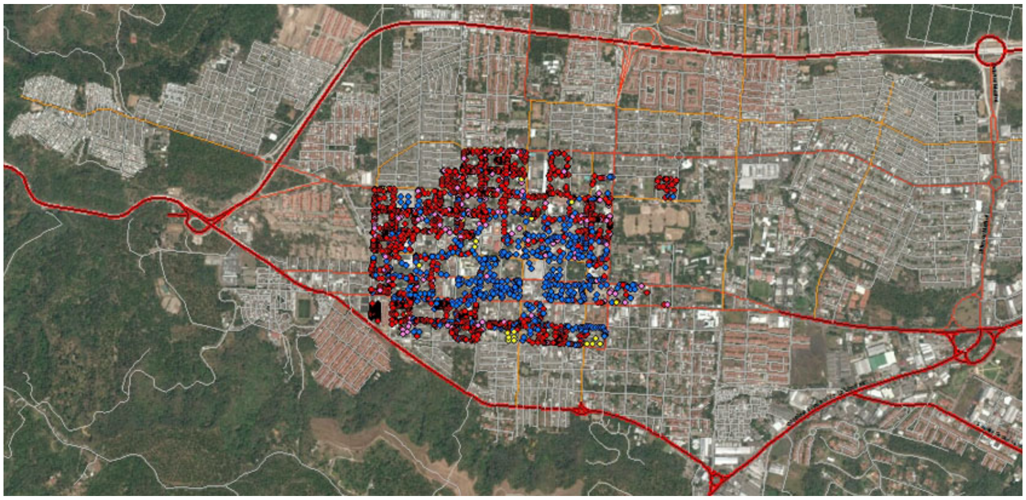


Fig. 5 - Surveyed structures at “Centro Historico”. Dot colors: Red: Housing; Blue: Business; Yellow: Industry and Purple: Other.

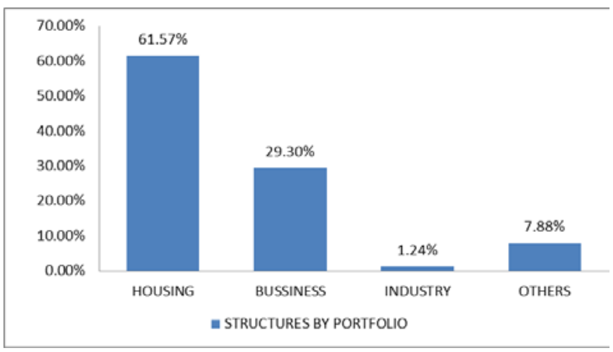


Fig. 6 - Structures of the “Centro Histórico” classified by portfolios.

The suburbs of Santa Tecla were surveyed by four groups. 664 exposed elements were selected to gather their information, as shown in Fig. 7. In this case, most of the structures fall into the portfolio “Housing”.

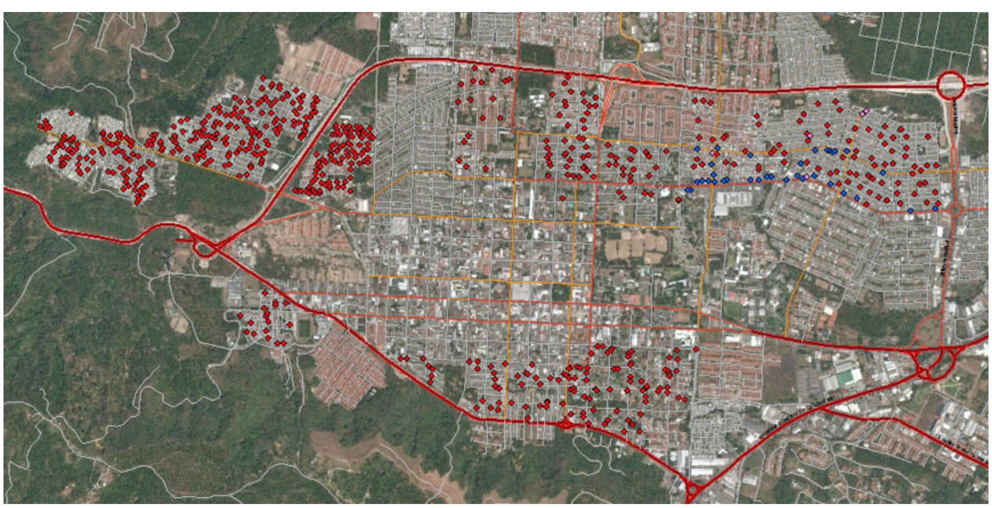


Fig. 7 - Surveyed structures at the suburbs of Santa Tecla. Dot colors: Red: Housing; Blue: Business; Yellow: Industry and Purple: Other.

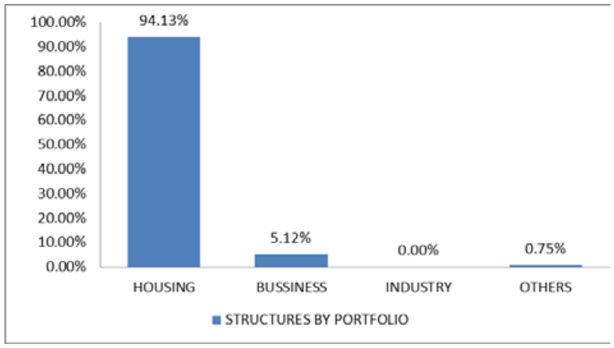


Fig. 8 – Exposed elements at the suburbs of Santa Tecla classified by portfolios.

More than 90% of the exposed elements assessed in this area falls into the portfolio “Housing” which is comprehensible since most of the structures are dwelling development projects, Fig. 8. Adding up all structures surveyed in both sub areas brings the total number of exposed elements to 2592. An important characteristic to know before performing any vulnerability analysis is the height of the edifice. Therefore, from statistics it can be noticed that most of the constructions are one or two-storey height, Fig. 9.

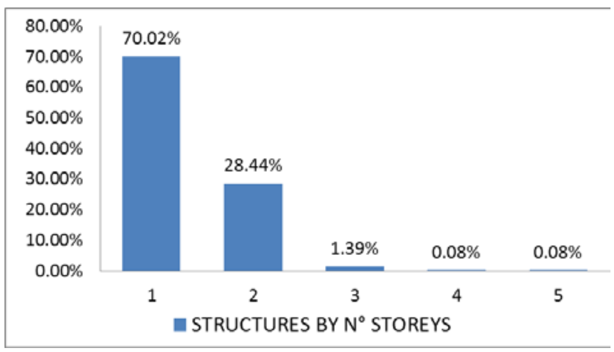


Fig. 9 - Structures classified by n° of storeys.

From the precedent paragraphs, the percentage of elements which their typologies are not included in the Vulnerability Table of [6] can be calculated. Table 3 shows that more than 5% of the structures cannot be assessed using the EMS-98, just for this case study alone. The reader has to keep in mind that Santa Tecla is located in the AMSS, as indicated before, and most of the dwellings are built using masonry walls; however, in the interior parts of El Salvador housing units are still constructed with the vernacular typologies such as Bahareque (which is also used in other parts of Central America under different names). From various seismic events, San Vicente 1936 [13], Jucuapa- Chinameca, 1951 [14], San Salvador, 1965 [15] and El Salvador, 2001 [16] Bahareque presents a wide range of seismic behavior that can span from falling of plaster, only, to total destruction; everything dependent on the maintenance of the wood and cane skeleton and the type of the roof. In [13] it is exposed that “Bahareque firmly rooted in the ground and adequately tied together, possesses structural unity as well as great elasticity, and is aseismic to a remarkable degree”; therefore, this typology might be worthy to be included into the EMS VC table in such a way that can take into account regional peculiarities in construction. Although, it has to be recognized that bahareque vulnerability has been successful catalogued using the EMS-98 previously [17].

Table 3 - Structural typologies not included in the Vulnerability Table of [6].

Typology	**Acronym**	**Percentage**
Bahareque	B	2.04
Light steel structure	PO	2.74
Precast structures	PR	0.12
Precarious structure	SP	0.46
TOTAL		**5.36**

Finally, using the procedure previously defined in 3, attributes of the structures belonging to the homogeneous block area were replicated into their respective urban blocks resulting in 16444 edifices. It is worth to mentioned that some information such as number of inhabitant per structures or their cost could not be collected from a number of areas due to many factors such as lack of access to the dwellings, distrust to the interviewer and lack of personal safety.

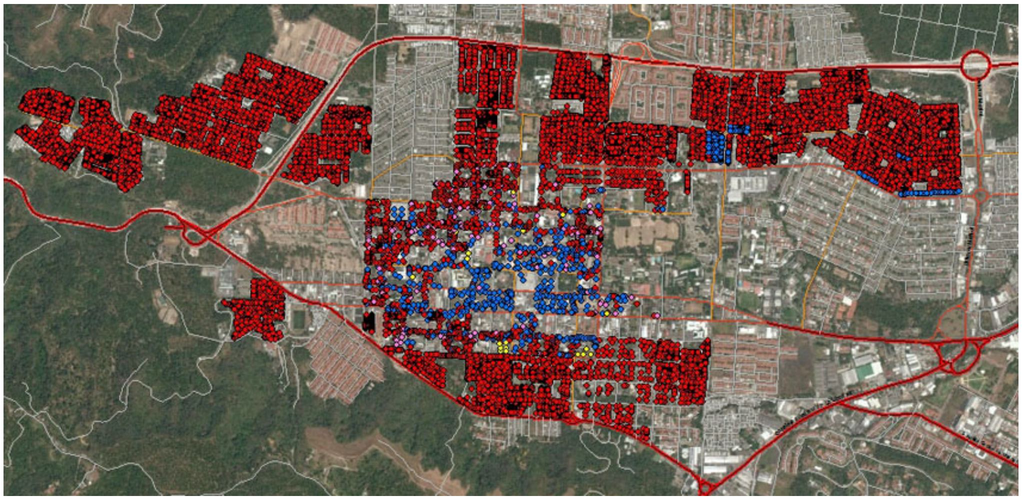


Fig. 10 - 16444 exposed elements to be used in the seismic risk assessment of Santa Tecla. Dot colors: Red: Housing; Blue: Business; Yellow: Industry and Purple: Other.

On the other hand, the procedure to develop the vulnerability curves depicted in the precedent section was carried out to compute the single storey, reinforced masonry walls structure curve set (PMR1) which includes the pre-code (PMR1-PC), low code (PMR1-LC) and medium-code (PMR1-MC) configurations. Fig. 11 illustrates the comparison between the three curve set obtained in previous projects, based on expert criteria mainly, and the one developed in this work for the PMR1 typology.

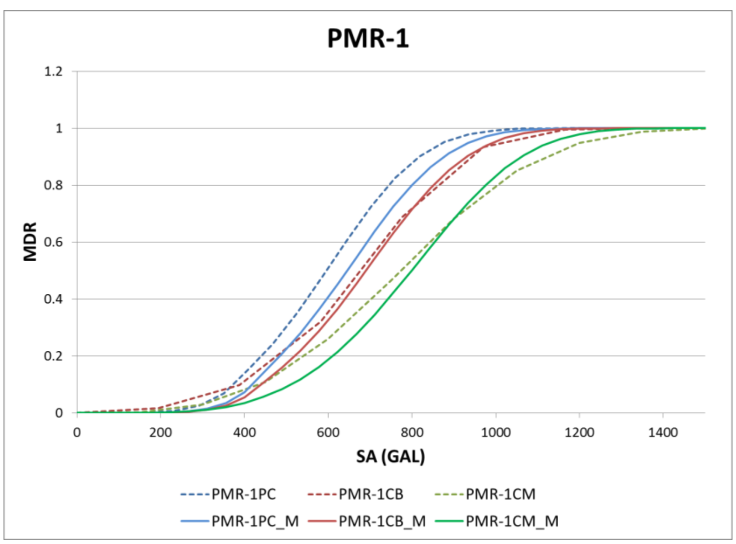
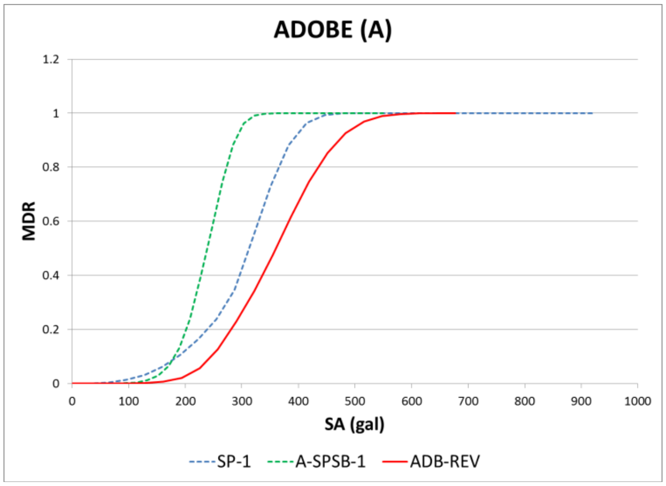


Fig. 11 - Vulnerability curves for single storey, reinforced masonry wall structure (PMR); PC, CB and CM stand for Pre-code, low code and medium code, respectively; M indicates the vulnerability curves developed in the present work.

Little difference can be observed, from the precedent figure, between the original and the modified vulnerability curves a result which can be explained considering that the behaviour of single-storey, reinforced masonry wall buildings is adequate known. However, this outcome will not be always true; making the same comparison for Adobe and Bahareque, differences between the curves developed before and the new ones is striking, Fig. 12.



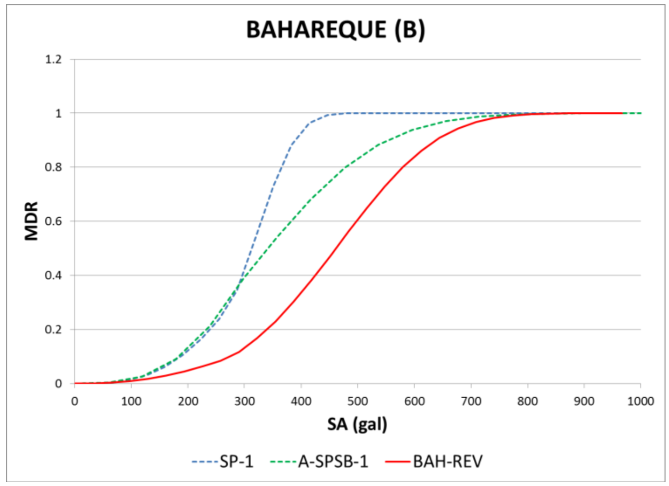


Fig. 12 - Vulnerability curves developed in this work, dotted line, and the ones developed in previous projects, continuous line, for (A) Adobe and (B) Bahareque. SP-1 is related to precarious structures and A-SPSB-1 is the curve assigned to single storey adobe structures by a previous project. ADB-REV and BAH-REV are the adobe and bahareque vulnerability curves, respectively, developed in the present work.

Following the procedure described in previous sections many of the typologies found in the study area has been reviewed. The main problem faced to perform these analyses has been the lack of information which can describe, in an accurate manner, the physical and mechanical characteristics of the materials, behaviour of assemblages and test executed on structural members which actually represents the Salvadoran typologies.

41 structural typologies have been found in Santa Tecla, new curves have been assigned to 29 due to the importance of the typologies and the large number of structures associated to them, accounting for 98% of the exposed buildings. 12 curves have been used without any modification, Table 4.

Table 4 - Structural typologies found in the study area.

MAIN TYPOLOGY	**CODE**	**N° OF STOREYS**
Structural typologies with modified or newly created vulnerability curves		
Steel braced frames (MACA)	Pre-code and Low	1
RC Moment resisting frame without seismic gap (MCSJ)	Pre-code, Low and Medium	1, 2-5
Moment resisting steel frames (MASA)	Low and Medium	1, 2-5
Bahareque (B)	Low	1
Light steel structure (PO)	Low and Medium	1
RC Structural walls (PCR)	Pre-code, Low and Medium	1, 2-5
Reinforced Masonry walls (including confined masonry walls) (PMR)	Pre-code, Low and Medium	1, 2-5
Wood (M)	Low and Medium	1
Adobe (A)	Low and Medium	1
Structural typologies with originally created vulnerability curves		
Steel braced frames (MACA)	Medium	2-5
RC Moment resisting frame with seismic gap (MCCJ)	Pre-code, Low and Medium	1, 2-5
Unreinforced masonry walls (PMSR)	Pre-code, Low and Medium	1, 2-5
Precast structures (PR)	Low	1
Precarious structure (SP)	Low	1

5. Conclusions

This is the first time that sufficient exposure information has been collected from an urban area in El Salvador, a fact which makes the main benefit of the research presented in this document. Structural defects, state of structures after historical earthquakes, typologies of structures, number of edifices belonging to a portfolio are some of the items compiled in a complete georeferenced database. On the vulnerability side, a set of vulnerability curves for a large group of structural typologies have been developed based on analytical computation which, it is believed, is more accurate than using "expert criteria".

There have been many other attempts to carry out similar procedures in the Metropolitan Area of San Salvador, and many other urban populations in the country, but all of them eventually have failed. The biggest blame can be put on the lack of cooperation from the governmental and municipal level to facilitate the information that they possess due, in some cases, to distrust towards the final goal of this kind of initiates, in some others, the little understanding about what to do with the final results and, in many others, the concern, from civil servants, about results which could suggest that they are ill prepare to face a seismic event.

The information produced in both areas, exposure and vulnerability, could be used primarily to perform a detailed seismic risk assessment. It is obvious that the main users of the results from these analyses will be the Municipality of Santa Tecla on one side, and Salvadoran Civil Protection Agency, on the other, which can then direct their relief efforts to areas that could be potential prone to seismic events. But the implications of the produced information could be extended to a wide range of applications such as identifying areas of the city where a particular pattern of structural defect is detected and utilizing the data to assess the risk to other types of hazards such as fire or landslides.

Throughout the process of assigning the structural typologies based on the Vulnerability Table of [6] it was quickly discovered the shortcomings of such classifications when used on the city of Santa Tecla. First, vernacular construction types widely found in the Central America cannot be catalogued, and, second, typologies such as steel structures and reinforced (or confined) masonry must have vulnerability classes based on the earthquake-resistant design capacity, similar to the RC structures. All of the above items can compromise the effective application of the EMS-98 to evaluate losses in the Central America area.

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