Paper 63. SEISMIC VULNERABILITY ASSESSMENT OF HISTORICAL CONSTRUCTIONS IN THE STATE OF COLIMA, MEXICO

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ABSTRACT

The main purpose of this paper is to analyze and compare different qualitative methodologies to assess the seismic vulnerability of historical constructions in the State of Colima, which is located in a seismic area. The vulnerability is assessed by empirical methods, including the vulnerability class method *(VCM)* and the vulnerability index method *(VIM*), in order to perform preliminary indicators of expected damage levels that allow the local authorities to take measures oriented to disaster prevention. Results from the assessment using both methodologies of fifteen historical masonry buildings, most of them from XIX century, are compared with a real vulnerability index of every building from observed damage after the 2003 M7.6 Colima earthquake, according to the classification of damage in masonry buildings (EMS-98).

1. INTRODUCTION

Most of the historical constructions located in the State of Colima, in Mexico, are churches, mainly built (or re-built) in the XIX century. They have the same colonial typology (see Figure 1), with variations in size and architectural sophistication. The local society has interest into preserve this cultural patrimony with its original characteristics, due to the architectural and historical importance that these buildings deserve.

In the seismological context, Colima distinguishes by its important exposure, being considered one of the Mexican states under most significant seismic hazard. The historical constructions belong to the groups more vulnerable to earthquakes, as demonstrated by the great damage suffered by this kind of constructions during the earthquake occurred at January 21, 2003 (magnitude 7.6). The Government of Mexico had to invest in expensive works of restoration and rebuilding, generating a restitution of the buildings' structural capacity and, in some cases, increasing their strength. Nevertheless, the safety level of each historical building, repaired or not after the 2003 earthquake, and the possible damage scenario at the occurrence of a larger magnitude earthquake, is completely unknown. Due to these circumstances, it is necessary to execute studies in order to know the seismic risk at the Colima State, and to assess the seismic vulnerability of the historical buildings. The final objective of these studies is to obtain indicators of expected damage levels that allow the local authorities to take measures oriented to disaster prevention.

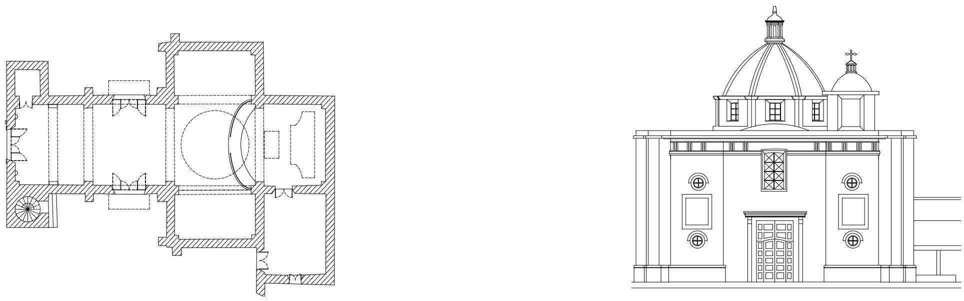

Figure 1. Plan view and façade of a typical Colima church

2. METHODOLOGY

As a first approach, the seismic vulnerability of fifteen historical masonry buildings was assessed in a qualitative way by empirical methods. The basis of these methods is the past experience about seismic behavior of different building typologies, and the characterization of potential structural deficiencies. The empirical methods include the vulnerability class method *(VCM)* and the vulnerability index method *(VIM)*.

The classification of structures used in the *VCM*, was the European Macroseismic Scale (EMS-98) [5]. Table 1.1 presents an EMS-98 summary, considering unreinforced masonry only. This proposal assigns a vulnerability class to every type of structure and it is considered as an efficient technique to assess the seismic vulnerability in a quick and satisfactory way. The EMS-98, classifies the different structural typologies in six vulnerability classes going from A to F, in function of the constructive materials used in the building (masonry, concrete, steel, or wood) and the level of seismic design. The first three classes A, B and C, represent the most vulnerable structural typologies (poor performance under earthquakes), such as walls made of adobe, rammed soil, mud and horizontal elements of wood, unconfined masonry walls made of natural stone, brick of fired clay, and frames made of reinforced concrete that were built without a seismic design. The D and E classes represent the medium vulnerable structural typologies (structures with seismic design), into this classification are well-built wooden structures, steel and reinforced concrete, confined and reinforced masonry. Finally the F class represents the less vulnerable structural typologies (structures with a high seismic design).

Table 1.1. Classification of structural typologies according to their vulnerability class (Summary of the EMS-98, considering only unconfined masonry)

Material	**Structural resistant system**	**Subtypes**	**Vulnerability Class**					
			A	**B**	**C**	**D**	**E**	**F**
Masonry	Walls made of natural stone	Walls made of rubble and mortar of mud	**X**					
		Walls made of stone and mortar of cement or hydrated lime			**X**			
	Walls made of soil (mud, adobe, and rammed soil)	Walls made of mud	**X**					
		Walls made of mud with horizontal elements of wood		**X**				
		Walls made of adobe	**X**					
		Walls made of rammed soil	**X**					
	Walls made of brick of fired clay	Unconfined walls and mortar of mud, cement or hydrated lime		**X**				
		Unconfined walls and mortar of mud, cement or hydrated lime (vertical and horizontal elements of wood)		**X**				
		Unconfined walls and mortar of mud, cement or hydrated lime (with slabs of concrete)			**X**			

The *VIM* used in this work is based on the GNDT [4], for unreinforced masonry buildings. This method allows the user to identify and characterize the potential structural deficiencies of a building, attributing numerical values (points) to each significant component, and determining, finally, a seismic vulnerability index. The GNDT method has been widely used in Italy during the last years, and it has been upgraded as a result of the continuous experimentation, resulting in an extensive database of damage and vulnerability. The parameters showed in Table 1.2, were compiled in a questionnaire to be applied during the field research. Based in past experiences, the questionnaire have suffered modifications, an example of this is the questionnaire developed by Aguiar et. Al. [1].

In this participation, a base questionnaire developed by Aguiar et. Al [1] was used. However, further modifications were proposed in order to assess buildings under particular conditions. Those modifications consisted particularly in:
Parameter 3: corresponding to conventional resistance, the proposal by Astroza et. Al [2] was adopted.
Parameter 4: soil types were adjusted to Mexican typical soil types (I, II, and III).

Parameter 7: Configuration of elevation. The ratio between total high (T) and bell tower high (H) was used to assign a vulnerability index:

A) $T/H \leq 0.2$ B) $0.2 < T/H \leq 0.3$ C) $0.3 < T/H \leq 0.5$ D) $T/H > 0.5$

Parameter 9: Typology of the roof. The possibility of Vaults was included

Table 1.2. Vulnerability index numerical scale (I_v) for unreinforced masonry buildings, [3]

i	**Parameter**	***Ki A***	***Ki B***	***Ki C***	***Ki D***	***Wi***
1	Organization of the resistant system	0	5	20	45	1.0
2	Quality of the resistant system	0	5	25	45	0.25
3	Conventional resistance	0	5	25	45	1.5
4	Position and foundation	0	5	25	45	0.75
5	Horizontal diaphragms	0	5	15	45	1.0
6	Floor configuration	0	5	25	45	0.5
7	Configuration of elevation	0	5	25	45	1.0
8	Maximum separation between walls	0	5	25	45	0.25
9	Typology of the roof	0	15	25	45	1.0
10	Non structural elements	0	0	25	45	0.25
11	Conservation level of the building	0	5	25	45	1.0

The use of Table 1.2 is simple, during the research in field is easy to choose one of the four classes A, B, C, or D, (A: Optimal, D: Awful). To every class corresponds a numerical value *Ki* varying between 0 and 45. Also, every parameter is affected for a coefficient of importance *Wi* varying between 0.25 and 1.5. This coefficient reflects the importance of each parameter inside the resistant system of the building, according to the opinion of experts. Next, the seismic vulnerability index (I_v), can be assessed with equation (1).

$$I_v = \sum_{i=1}^{11} K_i \cdot W_i \qquad (1)$$

Table 1.3. Ranks to assign the vulnerability class

Rank	**Vulnerability**
Iv < 15 %	Low
15 % $\leq$ Iv < 35 %	Medium
Iv $\geq$ 35 %	High

Analyzing Equation (1), it can be concluded that the vulnerability index defines a scale of values from 0 to the maximum value 382.5. It is divided by 3.825 to obtain a normalized value of vulnerability index, being the rank $0 < I_v < 100$. For a better interpretation of the results, the following ranks are represented as shown in Table 1.3, to assign a vulnerability class to each building.

3. RESULTS

Seismic vulnerability assessment by empirical methods was carried out in fifteen historical buildings in the State of Colima using two different approaches, the *VCM* and *VIM*.

3.1. Seismic vulnerability assessment of the buildings using the *VCM*

The application of the *VCM* consisted on a detailed surveying on everyone of the fifteen historical buildings, in order to obtain the vulnerability class related with the structural typology according to Table 1.1. This assessment was developed on the basis of the building's resistant system such as constructive materials, structural resistant system, structural subtypes; assigning to every building one of the vulnerability classes A, B, C, D, E, or F, being A the highest vulnerability class and F the lowest. It is very important to mention that the assessment was carried out taking in account additional information such as plans, constructive materials characteristics, historical analysis, structural description, previous intervention data and building's conservation level.

The vulnerability class results obtained for all of the fifteen historical buildings are illustrated in Table 1.4. Considering that classes A and B belongs to high vulnerability, C and D to medium vulnerability, E and F to low vulnerability, the results showed that thirteen buildings belong to the medium vulnerability interval and the remaining two were in the high vulnerability interval.

Table 1.4. Vulnerability class for every building

Name of the building	**Vulnerability Class**
Convent Ruins of *San Francisco de Almoloyan*	**C** (Medium)
Chapel of *Nuestra Señora de la Asuncion*	**B** (High)
Museum of Regional History of Colima	**C** (Medium)
Church of *San Felipe de Jesus*	**C** (Medium)
Church of *Nuestra Señora de la Merced*	**C** (Medium)
Cathedral *Basilica Menor de Guadalupe*	**C** (Medium)
Church of *San Pedro Apostol*	**C** (Medium)
Church of *San Miguel del Espiritu Santo*	**C** (Medium)
Church of *Sagrado Corazon de Jesus* (Colima City)	**C** (Medium)
Chapel of *Virgen del Refugio*	**C** (Medium)
Church of *San Jeronimo de los Santos Angeles*	**A** (High)
Church of *Sagrado Corazon de Jesus* (Town of Chiapa)	**C** (Medium)
Church of *San Jose*	**D** (Medium)
Church of *San Francisco de Asis*	**C** (Medium)
Church of *Nuestra Señora de la Salud*	**D** (Medium)

3.2. Seismic vulnerability assessment of the buildings using the *VIM*

Seismic vulnerability assessment by the *VIM* was applied. The procedure consisted on surveying carefully everyone of the fifteen historical buildings, in order to identify and characterize the potential structural deficiencies of the building corresponding to the eleven parameters shown in Table 1.2, assigning to every parameter one of the four classes A, B, C, or D (A: Optimal, D: Awful), attributing numerical values (points) to each significant component to determine with equation (1), the seismic vulnerability index (I_v), and finally, using Table 1.3 to assign a vulnerability class (high, medium or low) according to the ranks.

Four of the eleven parameters can't be evaluated during the surveying in field, these parameters are the conventional resistance, floor configuration, configuration of elevation and maximum separation between walls, to assess them, it is necessary to use computational tools to simplify the work as AutoCAD to obtain dimensions, elevations of the building, areas of the floors and vertical structural elements located in the *X* and *Y* direction, separation between walls, etc.

As in the *VCM* assessment, it was necessary to take into account additional information of every building. The vulnerability index (I_v) results obtained for all of the fifteen historical buildings are illustrated in Table 1.5.

Table 1.5. Vulnerability index for every building

Name of the building	I_v	I_v **%**	**Vulnerability**
Convent Ruins of *San Francisco de Almoloyan*	227.50	59.48	**(High)**
Chapel of *Nuestra Señora de la Asuncion*	158.75	41.50	**(High)**
Museum of Regional History of Colima	86.25	22.55	**(Medium)**
Church of *San Felipe de Jesus*	170.00	44.44	**(High)**
Church of *Nuestra Señora de la Merced*	175.00	45.75	**(High)**
Cathedral *Basilica Menor de Guadalupe*	186.25	48.69	**(High)**
Church of *San Pedro Apostol*	192.50	50.33	**(High)**
Church of *San Miguel del Espiritu Santo*	203.75	53.27	**(High)**
Church of *Sagrado Corazon de Jesus* (Colima City)	146.25	38.24	**(High)**
Chapel of *Virgen del Refugio*	166.25	43.46	**(High)**
Church of *San Jeronimo de los Santos Ángeles*	158.75	41.50	**(High)**
Church of *Sagrado Corazon de Jesus* (Town of Chiapa)	168.75	44.12	**(High)**
Church of *San Jose*	207.50	54.25	**(High)**
Church of *San Francisco de Asis*	175.00	45.75	**(High)**
Church of *Nuestra Señora de la Salud*	170.00	44.44	**(High)**

The results illustrated in Table 1.5. were different than those of the first approach, fourteen buildings obtained a high vulnerability index, while just only one obtained a medium vulnerability index.

Table 1.6. Classification of observed damage according to the (EMS-98), [5]

Name of the building	Damage (EMS-98)	Vulnerability
Convent Ruins of *San Francisco de Almoloyan*	Grado 3	**(High)**
Chapel of *Nuestra Señora de la Asuncion*	Grado 3	**(High)**
Museum of Regional History of Colima	Grado 2	**(Medium)**
Church of *San Felipe de Jesus*	Grado 2	**(Medium)**
Church of *Nuestra Señora de la Merced*	Grado 2	**(Medium)**
Cathedral *Basilica Menor de Guadalupe*	Grado 3	**(High)**
Church of *San Pedro Apostol*	Grado 4	**(High)**
Church of *San Miguel del Espiritu Santo*	Grado 3	**(High)**
Church of *Sagrado Corazon de Jesus* (Colima City)	Grado 4	**(High)**
Chapel of *Virgen del Refugio*	Grado 2	**(Medium)**
Church of *San Jeronimo de los Santos Angeles*	Grado 3	**(High)**
Church of *Sagrado Corazon de Jesus* (Town of Chiapa)	Grado 3	**(High)**
Church of *San Jose*	Grado 3	**(High)**
Church of *San Francisco de Asis*	Grado 3	**(High)**
Church of *Nuestra Señora de la Salud*	Grado 2	**(Medium)**

Grade 1: Negligible to slight damage (No structural damage, slight non-structural damage), Grade 2: Moderate damage (Slight structural damage, moderate non-structural damage), Grade 3: Substantial to heavy damage (Moderate structural damage, heavy non-structural damage), Grade 4: Very heavy damage (Heavy structural damage, very heavy non-structural damage), Grade 5: Destruction (Very heavy structural damage).

For a better interpretation and comparison of the results, the classification of damage according to the (EMS-98) for every building (grade 1, 2, 3, 4 and 5), was classified in three groups, in order to assign a vulnerability class as shown in Table 1.7.

Table 1.7. Ranks to assign the vulnerability class

Damage (EMS-98)	Vulnerability
Grade 1	Low
Grade 2	Medium
Grade 3, 4 and 5	High

4. CONCLUSION

Seismic vulnerability of fifteen different buildings was evaluated under two different approaches: Vulnerability class method *(VCM)* and the Vulnerability index method *(VIM)*. It is important to mention that a real vulnerability index of every building was also available from the observed damage after the 2003 M7.6 Colima earthquake, according to the classification of damage in masonry buildings (EMS-98), as shown in Table 1.6. The results obtained by both assessment methods were analyzed and it was concluded that *VIM* provided more accurate results. The fourteen high vulnerability buildings identified by *VIM* are the buildings that suffered stronger damage during the 2003 earthquake. The *VCM* prediction was poor and the authors consider it not trustable. However, the *VIM* allows the user to perform a preliminary vulnerability assessment in a satisfactory and quick way. In a next stage of this research, the buildings that obtained a higher vulnerability index will be assessed again using quantitative methodologies such as a combination of analytical (theoretical) and experimental methods, in order to obtain and compare a different series of methods.

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