2014-12-09

A correlation between damage and intensity on old masonry churches in Colima, Mexico by the 2003 M7.5 earthquake

Preciado, Adolfo; Orduña, Agustín

Preciado, A. and Orduña, A. (2014). "A Correlation Between Damage and Intensity on Old Masonry Churches in Colima, Mexico by the 2003 M7.5 Earthquake". Journal of Case Studies in Structural Engineering, 2: pp. 1-8

Case Studies in Structural Engineering 2 (2014) 1–8

Contents lists available at ScienceDirect

Case Studies in Structural Engineering

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

A correlation between damage and intensity on old masonry churches in Colima, Mexico by the 2003 M7.5 earthquake

A. Preciado [a,*], A. Orduña [b]

[a] Polytechnical University of Guadalajara, Mexico
[b] University of Colima, Mexico

ARTICLE INFO

Article history:
Available online 27 June 2014

Keywords:
Vulnerability
Damage assessment
Earthquakes
Old masonry
Intensity
Churches

ABSTRACT

Strong damage was observed in Colima Mexico on most of the cultural patrimony (mainly churches) after the 2003 M7.5 earthquake. In order to find a correlation between the observed damage on the historical buildings and the earthquake intensity, the vulnerability is assessed by qualitative methods, including the vulnerability class method (VCM) and the vulnerability index method (VIM). The latter method is modified and adapted in this research to assess the seismic vulnerability of historical buildings such as churches and cathedrals located in areas from high to very high seismicity. The results are intended to serve as preliminary indicators of expected damage levels that allow the local authorities to take measures oriented to disaster prevention. The assessment using both methodologies is developed on 15 historical masonry churches, most of them from XIX century. With the results, a correlation between damage and intensity taking into account a Macroseismic Scale is developed and the qualitative methodologies to assess the seismic vulnerability of historical constructions are compared each other.

Introduction

Most of the historical constructions located in the State of Colima, Mexico are churches, mainly built (or re-built) in the XIX century. They have the same colonial typology with variations in size and architectural sophistication (see Fig. 1). The local society has a special interest to preserve this cultural patrimony with its original characteristics, due to the architectural and historical importance that these structures represent for the people and authorities. In the seismological context, Colima is distinguished 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 (EQ), as demonstrated by the great damage suffered by this type of constructions (see Fig. 2) during the EQ occurred at January 21st, 2003 (M7.5). The Government of Mexico had to invest in expensive works of restoration and rebuilding, generating a restitution of the structural capacity of the church, and in some cases, increasing their strength. Nevertheless, the safety level of each historical building repaired or not after the 2003 EQ, and the possible damage scenario at the occurrence of a larger magnitude EQ is completely unknown. Due to these circumstances, a research project was carried out with the main objective to assess the vulnerability of the historical constructions in Colima State. The main objective of this project is to obtain indicators of expected damage levels that allow the local authorities to take measures oriented to disaster of this prevention. In a first phase research, the

* Corresponding author. Address: Polytechnical University of Guadalajara, Km 3.5 Carretera Santa Fe – Tlajomulco, Guadalajara, Mexico. Tel.: +52 3316696432.

E-mail address: preciadoqa@yahoo.es (A. Preciado).

http://dx.doi.org/10.1016/j.csse.2014.05.001
2214-3998/© 2014 The Authors. Published by Elsevier Ltd.

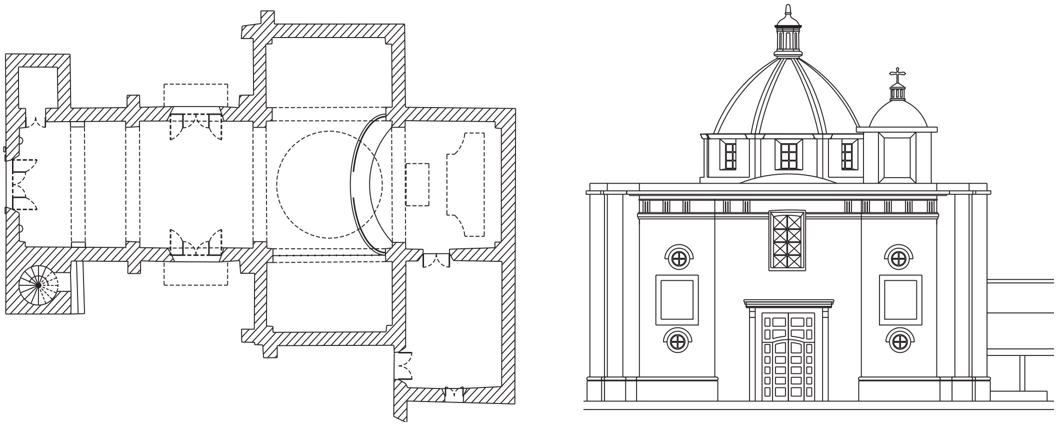

Fig. 1. Plan view and façade of a typical Colima church.

Fig. 2. Observed damages on churches after the 2003 M7.5 Colima, Mexico EQ.

seismic vulnerability of the constructions was assessed through qualitative methods and in a subsequent phase, a correlation between damage and intensity was carried out with the results. This paper presents the procedure used to assess the seismic vulnerability of 15 selected historical churches located in Colima by means of qualitative methodologies such as vulnerability class method (VCM) and the vulnerability index method (VIM). With the results, a correlation between damage and intensity taking into account the European Macroseismic Scale (EMS) developed by [1] is carried out. [2] affirm that this scale represents a very significant effort to relate damage over a series of construction types with different seismic intensities. Here, damage and intensity have different levels assigned in qualitative terms.

Methodology

The seismic vulnerability of 15 historical masonry churches is assessed in a qualitative way by qualitative 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 qualitative methods include the vulnerability class method (VCM) and the vulnerability index method (VIM). The classification of structures used in the VCM is the EMS [1]. Table 1 presents a summary of the scale, 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 fast and satisfactory way. The EMS, classifies the different structural typologies in six vulnerability classes going from A to F (A: high vulnerability, F: low vulnerability) in function of the construction materials used in the building (masonry, concrete, steel, or wood) and the level of seismic design. For masonry buildings the first three classes A, B and C represent structural typologies such as walls made of rubble stone, fieldstone, adobe, simple stone, massive stone, unreinforced manufactured units and unreinforced masonry with reinforced concrete floors. The D class represents reinforced or confined masonry.

The VIM used in this work is based on the proposed by [3] and [4], for unreinforced masonry buildings. This method allows the user to identify and characterize the potential structural deficiencies of a building, attributing numerical values

Table 1
Summary of the classifications used in the European Macroseismic Scale [1]. Differentiation of structures (buildings) into vulnerability classes.

Type of structure		Vulnerability class					
		A	B	C	D	E	F
MASONRY	Rubble stone, fieldstone	X					
	Adobe (earth brick)	X	1				
	Simple stone	0	X				
	Massive stone		1	X	0		
	Unreinforced, with manufactured units	0	X	0			
	Unreinforced, with reinforced concrete floors		1	X	0		
	Reinforced or confined			0	X	1	

X: most likely vulnerability class, 1: probable range, 0: range of less probable, exceptional cases.

Table 2
Vulnerability index numerical scale (I_v) for unreinforced masonry buildings [4].

i	Parameter	K_i A	K_i B	K_i C	K_i D	W_i
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

(points) to each significant component, and determining with this a seismic vulnerability index. The GNDT method has been widely used in Italy during last year and it has been upgraded because of the continuous experimentation, resulting in an extensive database of damage and vulnerability. The parameters showed in Table 2, were compiled in a questionnaire to be applied during the field research. Based on experience, the questionnaire have undergone modifications, an example of this is the questionnaire developed by [5]. In this participation, a base questionnaire developed by [5] was used. However, further modifications were proposed by [6] in order to assess buildings under particular conditions such as historical buildings of patrimonial importance located in high seismic areas. Those modifications consisted particularly in:

- Parameter 3: corresponding to conventional resistance, the proposal by [7] 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 height (T) and bell tower height (H) was used to assign a vulnerability index: (A) $T/H \leqslant 0.2$, (B) $0.2 < T/H \leqslant 0.3$, (C) $0.3 < T/H \leqslant 0.5$, (D) $T/H > 0.5$.
- Parameter 9: typology of the roof. The possibility of vaults, cupolas, and other types of heavy masonry roofs characteristic of historical constructions were included.

The use of Table 2 is simple, during the field research is selected one of the four classes A, B, C, or D (A: low vulnerability, D: high vulnerability). To every class corresponds a numerical value K_i varying between 0 and 45. In addition, every parameter is affected for a coefficient of importance W_i 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 Eq. (1).

$$I_v = \sum_{i=1}^{11} K_i \cdot W_i \tag{1}$$

Analyzing Eq. (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 $0 < I_v < 100$.

Seismic vulnerability assessment

As a first phase of the research project, the seismic vulnerability assessment by qualitative methods was carried out in 15 historical churches in the State of Colima using two different approaches, the VCM and VIM. The assessment of the churches was made for two scenarios, before and after the EQ occurred at January 21st, 2003 (M7.5).

Seismic vulnerability assessment of the buildings using the VCM

The implementation of the VCM consisted on a detailed survey of every one of the 15 historical buildings in order to obtain the vulnerability class related with the structural typology according to Table 1. This assessment was developed on the basis of the building's resistant system such as construction materials, 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 into account additional information such as plans, construction materials characteristics, historical analysis (damages and restoration), structural configuration and connection, previous interventions and building's conservation level. These parameters allowed taking into account in the assessment the probabilistic ranges shown in Table 1. The seismic vulnerability of the 15 churches using the VCM was assessed in a first instance before the 2003 EQ (Table 3) to consider a non-damage scenario. The results in Table 3 represent that eight of the churches belong to the class A, which represents a high vulnerability, subsequently, five churches obtained a class B and the rest belong to the class C. This means that the churches before the EQ had a deficient conservation level, damages suffered for the churches in previous EQs, heavy and tall bell towers made of original materials. All these parameters contributed with the high seismic vulnerability of every building. The seismic vulnerability of the churches using the VCM was assessed in a second stage after the 2003 EQ (Table 3) to consider a damage scenario. The results showed that five of the churches belong to the most vulnerable class, A, eight of the churches obtained a class B and the last 2 a class C. The high vulnerability of the churches decreased due to the restoration of the churches after the 2003 EQ. The conservation level of the churches improved and the connection between structural elements, the tall and heavy bell towers of some churches collapsed or were removed after the EQ and changed for light ones. That improved in a certain way the seismic vulnerability of most of the churches.

Seismic vulnerability assessment of the buildings using the VIM

The seismic vulnerability assessment of the 15 buildings was developed by the VIM. The procedure consisted on a detailed survey of everyone of the 15 historical buildings to identify and characterize potential structural deficiencies as stated at the eleven parameters shown in Table 2. For every one of the parameters is assigned one of the four classes A, B, C, or D (A: low vulnerability, D: high vulnerability) attributing numerical values (points) to each significant component to determine with Eq. (1) the seismic vulnerability index (I_v). Four of the eleven parameters are not so easy to evaluate during the field surveys. These parameters correspond to the conventional resistance, floor configuration, configuration of elevation and maximum separation between walls. To assess them, it is necessary the 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 (see Fig. 1). The seismic vulnerability of the churches using the VIM was assessed before and after the 2003 EQ to consider two damage scenarios. As in the VCM assessment, it was necessary to take into account additional information of every building such as plans, construction materials characteristics, historical analysis (damages and restoration), structural configuration and connection, previous intervention data and building's conservation level. The vulnerability index (I_v) results obtained for all of the 15 historical churches before and after the 2003 EQ are illustrated in Table 3. The results represent that the vulnerability index of the buildings was elevated before the EQ and it reduced after the restoration works. In most of the churches, some of the potential structural deficiencies were corrected, such as conservation level, connection between structural elements and heavy bell towers. This restoration contributed to decrease satisfactory the seismic vulnerability index of most of the buildings.

Table 3
Vulnerability class and index for every church before and after the 2003 EQ.

Name of the building	Before the EQ		After the EQ	
	V.C.	I_v %	V.C.	I_v %
Convent Ruins of San Francisco de Almoloyan	A	59.48	A	59.48
Chapel of Nuestra Señora de la Asuncion	A	46.73	B	41.50
Museum of Regional History of Colima	B	22.55	B	22.55
Church of San Felipe de Jesus	B	49.67	B	44.44
Church of Nuestra Señora de la Merced	B	39.22	B	39.22
Cathedral Basilica Menor de Guadalupe	B	48.69	B	48.69
Church of San Pedro Apostol	A	55.56	A	43.79
Church of San Miguel del Espiritu Santo	A	59.80	A	53.27
Church of Sagrado Corazon de Jesus	A	50	B	31.70
Chapel of Virgen del Refugio	A	50	B	43.46
Church of San Jeronimo de los Santos Angeles	A	48.04	A	41.50
Church of Sagrado Corazon de Jesus	B	44.12	B	44.12
Church of San Jose	C	54.25	C	54.25
Church of San Francisco de Asis	A	50.98	A	45.75
Church of Nuestra Señora de la Salud	C	49.67	C	44.44

V.C.: vulnerability class, I_v: vulnerability index %.

Correlation between damage and intensity

The intensities after the 2003 Colima EQ (M7.5) were mainly assessed taking into account reports made by the authorities, field inspections made by experts, news, and interviews. The Scale used was the Mercalli Modified Intensity (MMI). The region with the maximum intensity was the state of Colima (VIII). It is important to mention that intensities bigger than VII have only occurred approximately seven times in 100 years [8]. The results from the assessment using both methodologies VCM and VIM on the 15 historical masonry churches are taken into account to develop a correlation between damage and intensity by means of the EMS. The Scale allows correlating damage with the intensity of an EQ in the MMI Scale. The correlation takes into account the seismic vulnerability class of the building (VCM) and the intensity, assigning an expected damage based on the classification of observed damage in masonry buildings after an EQ. The observed damage in every building showed after the 2003 EQ (Table 4) could be categorized taking into account the classification of observed damage in masonry buildings described in the scale EMS. For the assessment of the observed damage, it was necessary a survey of every building after the EQ and extra information such as photographs, and general information. The EMS classifies the observed damage in masonry buildings after an EQ into five categories. 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). The results showed in Table 4 represent the estimated intensity in every building before and after the EQ (VIII); the observed damage; the vulnerability class assessed by the VCM; and the expected damage taking into account the correlation between intensity and vulnerability. The results showed in Fig. 3 represent the observed damage Vs expected damage before the 2003 EQ. For a better understanding of the results, the number of coincidences between the number of churches (scale of the graphic points) with an observed damage and an equal or close expected damage were organized in groups. Two churches obtained an observed damage 4 and an expected damage 4, four churches an observed damage 2 and an expected damage 3, five churches an observed damage 3 and an expected damage 4, the rest of the churches were dismissed (just one equal or close coincidence). Taking into account the results, the authors conclude that for this assessment before the EQ, the expected damage is one grade over the observed damage. For example if the observed damage of the building is 3, it was expected to be a damage of Grade 4. Fig. 4 represents the results of the observed damage Vs expected damage after the 2003 EQ. Taking into account the same methodology as in Fig. 3, two churches obtained an observed damage 3 and an expected damage 3, four churches an observed damage 3 and an expected damage 4, five churches an observed damage 2 and an expected damage 3, the rest of the churches were dismissed (just one equal or close coincidence). Analyzing the results, the authors conclude that in this assessment after the EQ, the expected damage is one grade over the observed damage. The notable difference between the results before and after the EQ is that the seismic vulnerability of the churches reduced 1 grade of expected damage due to the restoration campaigns. The assessment of the churches made by the VIM before and after the 2003 EQ could be correlated with the damage and the intensity of the EQ, taking into account as in the VCM the observed damage in every building based on the classification of the EMS. The results showed in Table 4 represent the observed damage in every building after the EQ (intensity VIII) and the vulnerability index percentage. The results of Fig. 5 represent the observed damage vs. vulnerability index percentage before the 2003 EQ. The average vulnerability index for the churches with an observed damage 2, is 42.54 (40% of the churches), observed damage 3, 52.57 (46.67% of the churches) and finally observed damage 4, 52.78 (13.33% of the churches). Taking into account the results, it is worth noting that an observed damage or expected damage of 2 may be presented in churches with a vulnerability index close of 40,

Table 4
Comparison of indicators before and after the 2003 EQ for every church.

Name of the building	EQ I	Before the EQ			After the EQ		
		O.D.	V.C.	E.D.	O.D.	V.C.	E.D.
Convent Ruins of San Francisco de Almoloyan	VIII	3	A	4	3	A	4
Chapel of Nuestra Señora de la Asuncion	VIII	3	A	4	3	B	3
Museum of Regional History of Colima	VIII	2	B	3	2	B	3
Church of San Felipe de Jesus	VIII	2	B	3	2	B	3
Church of Nuestra Señora de la Merced	VIII	2	B	3	2	B	3
Cathedral Basilica Menor de Guadalupe	VIII	3	B	3	3	B	3
Church of San Pedro Apostol	VIII	4	A	4	4	A	4
Church of San Miguel del Espiritu Santo	VIII	3	A	4	3	A	4
Church of Sagrado Corazon de Jesus	VIII	4	A	4	4	B	3
Chapel of Virgen del Refugio	VIII	2	A	4	2	B	3
Church of San Jeronimo de los Santos Angeles	VIII	3	A	4	3	A	4
Church of Sagrado Corazon de Jesus	VIII	2	B	3	2	B	3
Church of San Jose	VIII	3	C	2	3	C	2
Church of San Francisco de Asis	VIII	3	A	4	3	A	4
Church of Nuestra Señora de la Salud	VIII	2	C	2	2	C	2

I: 2003 EQ Intensity, O.D.: observed damage, V.C.: vulnerability class, E.D.: expected damage.

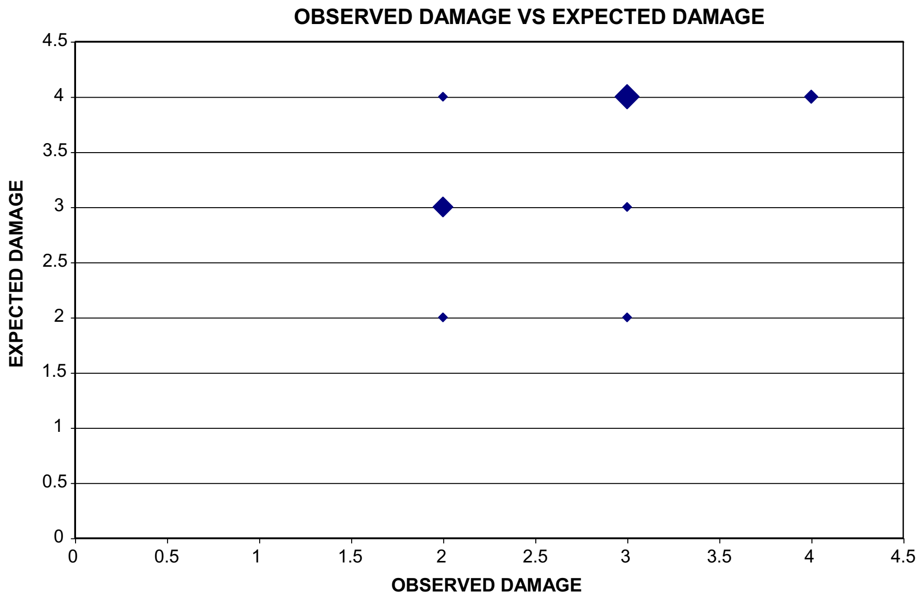

Fig. 3. Observed damage vs. expected damage before the 2003 EQ.

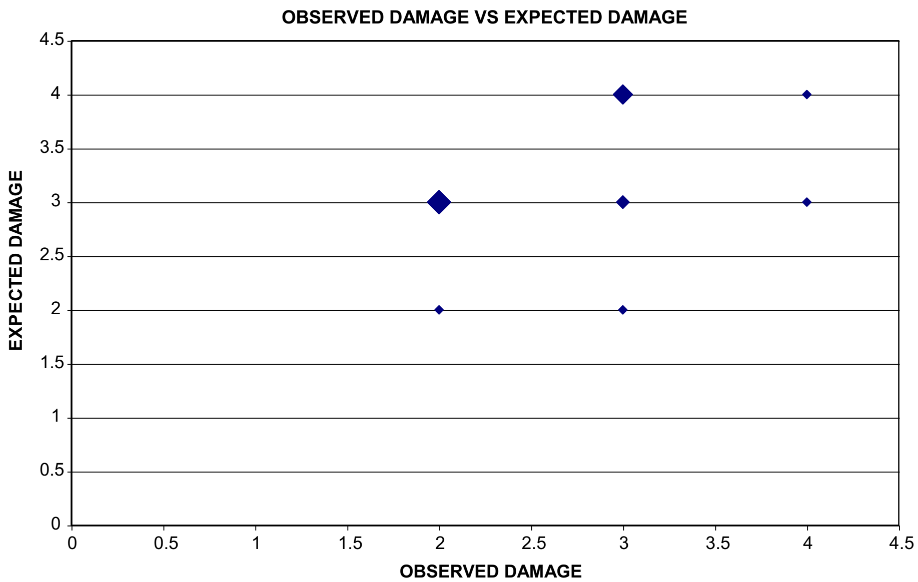

Fig. 4. Observed damage vs. expected damage after the 2003 EQ.

an observed damage of 3 for a vulnerability index close of 50, and finally an observed damage of 4 for churches with a vulnerability index bigger than 50. The scale of the points (Fig. 5) in the graphics represents the churches that were assessed with the same vulnerability index and observed damage. The results showed in Fig. 6 represent the observed damage vs. vulnerability index in percentage after the 2003 EQ. The average vulnerability index for the churches with an observed damage 2 is 39.71 (40% of the churches), observed damage 3 is 49.21 (46.67% of the churches) and finally observed damage 4, 37.75 (13.33% of the churches). Analyzing the results, it is important to note that an observed damage or expected damage of 2 may be presented in churches with a vulnerability index close of 40, an observed damage of 3 for a vulnerability index close of 50, and finally an observed damage of 4 for churches with a vulnerability index close of 40. The discontinuity between observed damage 3 and 4 means that the churches with an observed damage of 4 were the most damaged of all the evaluated conjunct, and due to this, their bell towers suffered strong damage or collapse. Their vulnerability index was reduced by the implementation of light materials at the heavy and vulnerable towers.

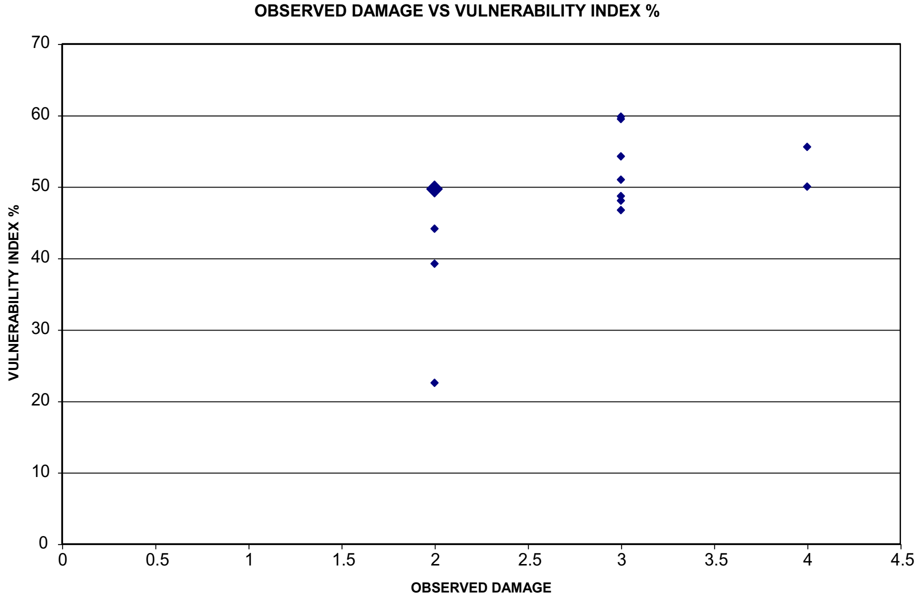

Fig. 5. Observed damage vs. vulnerability index before the 2003 EQ.

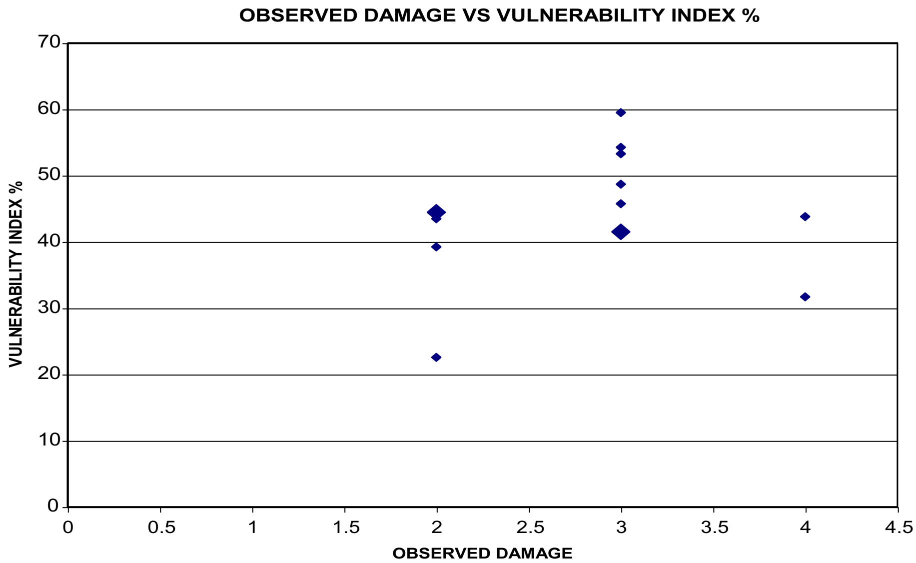

Fig. 6. Observed damage vs. vulnerability index after the 2003 EQ.

Conclusions

The seismic vulnerability of 15 different churches was evaluated for two damage scenarios (before and after the 2003 M7.5 Colima EQ) under two different approaches, VCM and VIM. It is important to mention that a real vulnerability index of every building was also available from the observed damage after the EQ, according to the classification of damage in masonry churches of the EMS. The results obtained by both assessment methods were analyzed and it was concluded that the VCM allows the user to evaluate the seismic vulnerability in a faster way than the VIM, but the results indicate a global vulnerability, nevertheless, the VIM allows an identification of the most vulnerable components of a historical building during an EQ. Both methods could be used to obtain the vulnerability of a church in a qualitative way, in order to obtain indicators of expected damage. The churches identified with a high vulnerability may be assessed in a quantitative way by means of more accurate and quantitative methods such as FEM and limit analysis. These refined methodologies allow to be obtained results more realistic and reliable and a detailed location of damage after a certain EQ, assessing the seismic performance of the building and failure mechanisms. A correlation between both methodologies with damage and intensity was also possible taking into account the EMS. In the VCM, the expected damage was obtained taking into account the vulnerability class of every building. It was observed that it is one grade over the observed damage for both cases, before and after the EQ. It indicates that an expected damage of a building may be assessed in an accurate way, reducing one grade the obtained expected damage. Based on the correlation between damage and intensity with the VIM assessed before the EQ, it could be concluded that an observed damage (or expected damage) of 2 could occur in churches with a vulnerability index close to 40, damage 3 for an index close to 50, and an damage 4 for churches with a vulnerability index bigger than 50. It indicates as in the VCM results that a defined expected damage could occur depending of the vulnerability index of the building. For the VIM assessed after the EQ, the results for observed damage 2 and 3 are similar than in the assessment before the EQ. The only difference is that churches with an observed damage of 4, the vulnerability index is close to 40. The discontinuity between observed damage 3 and 4 means that the churches with an observed damage of 4 were the most damaged of all, and due to this, their bell towers suffered strong damage or collapsed, and were substituted for others made by conventional and light materials, reducing their seismic vulnerability index. The authors of this paper consider the results of the assessment after the EQ using the VIM as not completely reliable, because it could be for necessary another EQ to obtain a new observed damage in every church and compare the results evaluated with the VIM of the repaired churches.

References

[1] Grünthal G. European Macroseismic Scale EMS 1998. European Council. Notes of the European center of geodynamics and seismology; 1998.
[2] Orduña A, Preciado A, Galván JF, Araiza JC. Vulnerability assessment of churches at Colima by 3D limit analysis models. In: Proceedings of the 6th international conference on structural analysis of historical constructions (SAHC), Bath, UK, July 2–4; 2008.
[3] GNDT. Seismic risk of public buildings. National Council of Investigation. National Group for the defense of earthquakes (GNDT). Methodology Aspects; 1990.
[4] Benedetti D, Petrini V. Seismic vulnerability of masonry buildings: proposition of an assessment methodology. The Construction Industry, No. 149, Rome, Italy; 1984.
[5] Aguiar R, Barbat A, Caicedo C, Canas J. Seismic vulnerability of buildings (in Spanish). Monographs of seismic engineering. Barcelona, Spain: Published by the International Center of Numerical Methods (CIMNE); 1994.
[6] Preciado A. Seismic vulnerability assessment of historical constructions in the state of Colima, Mexico (in Spanish). Master Thesis, Universidad de Colima, Mexico; 2007.
[7] Astroza M, Moroni MO, Küpfer M. Seismic assessment of brick masonry confined with elements of reinforced concrete. 26th South American Congress on Structural Engineering, Uruguay, vol. 1; 2006. p. 327–38.
[8] EERI and SMIS. The earthquake of Colima, Mexico occurred at January 21, 2003. SMIS and EERI reports (learning from the earthquakes).