

VULNERABILITY ASSESSMENT OF ITALIAN UNREINFORCED MASONRY CHURCHES USING MULTI-LINEAR REGRESSION MODELS

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Abstract. *The extensive damage occurred to the Italian historical and architectural heritage during the 2016-2017 earthquake sequence, and particularly to unreinforced masonry churches, highlights the need to better recognize the vulnerability of religious buildings. A sample of 158 churches belonging to the four stricken regions is studied and their performance analysed statistically. Structural behaviour of these churches is described in terms of mechanisms affecting the so-called macroelements, being portions of the building behaving more or less independently. In order to define fragility curves correlating the damage related to each collapse mechanism against ground motion intensity and churches' specific characteristics, the observed behaviour of the sample is herein analysed by means of statistical procedures accounting for possible local collapse mechanisms. Several regressions strategies are considered, accounting for vulnerability modifiers increasing/reducing the vulnerability of each macroelement, since the severity of shaking alone is not capable to fully explain the observed damage, strongly influenced by structural details that can worsen the seismic performance or improve it through earthquake-resistant elements. A synthetic damage index, purely based on observed data, is used to summarise the overall severity of damage related to relevant mechanisms, highlighting the contributions of ground shaking and building vulnerability. Results show the relevance of the proposed multi-linear regression models for the national heritage of churches and the advisability of extending mechanism-based regressions to other countries besides Italy. The proposed global damage index can be used as predictive tool to support seismic vulnerability mitigation at a territorial scale.*

1 INTRODUCTION

In 2016-2017 a strong seismic sequence struck a wide area of Central Italy within the boundaries of Latium, Abruzzi, Umbria and Marche regions (Figure 1), causing severe damage and hundreds of casualties. The first two events, occurred on August 24 (M_w 6.0 and 5.4) caused 299 fatalities and several hundreds of injuries, mostly affecting the municipalities of Amatrice, Arquata del Tronto, and Accumoli. The strongest event took place on October 30, 2016 (M_w 6.5) and caused extensive damage to the municipalities of Norcia and Castelsantangelo sul Nera, with no further fatalities.

The building portfolio of the affected area is characterised by numerous historical constructions, which were strongly damaged by the seismic swarm. The October event was particularly destructive for the religious buildings in the city of Norcia, where almost all churches suffered extensive damage and collapses [1]. In fact, it is widely known that churches frequently exhibit a seismic vulnerability higher than ordinary buildings [2], because of their architectural and structural characteristics such as open plan, large wall height-to-thickness and length-to-thickness ratios, and the use of thrusting horizontal structural elements for vaults and roofs [3]. As known, historical unreinforced masonry (URM) buildings, and particularly churches, tend to respond to earthquakes with local mechanisms rather than with a global behaviour, with a set of different architectural components, commonly called macro-elements, behaving more or less independently one from the adjacent [4–7]. According to such observation, the behaviour of a sample of 158 URM churches is herein analysed accounting for 28 possible local collapse mechanisms (Table 1), as currently adopted in Italy for post-earthquake assessment of churches [8]. In order to correlate the observed damage related to each collapse mechanism against ground motion intensity and churches' specific characteristics, several statistical procedures are used.

Table 1: List of the possible 28 collapse mechanisms

Ref. no.	Description	Ref. no.	
1	Overturning of the façade	15	Roof lantern
2	Gable mechanisms	16	Overturning of the apse
3	Shear in the façade	17	Shear in the apse
4	Damage in the porch	18	Vaults in the apse
5	Transversal response of the nave	19	Interactions between the nave and its roof
6	Shear in longitudinal walls	20	Interactions between the transept and its roof
7	Longitudinal response of the columns	21	Interactions between the apse and its roof
8	Vaults in the main nave	22	Overturning of the chapels
9	Vaults in the aisles	23	Shear in the chapels
10	Overturning of the transept	24	Vaults in the chapels
11	Shear in the transept	25	Interactions next to irregularities
12	Vaults in the transept	26	Projections
13	Triumphal arch	27	Bell tower
14	Dome	28	Belfry

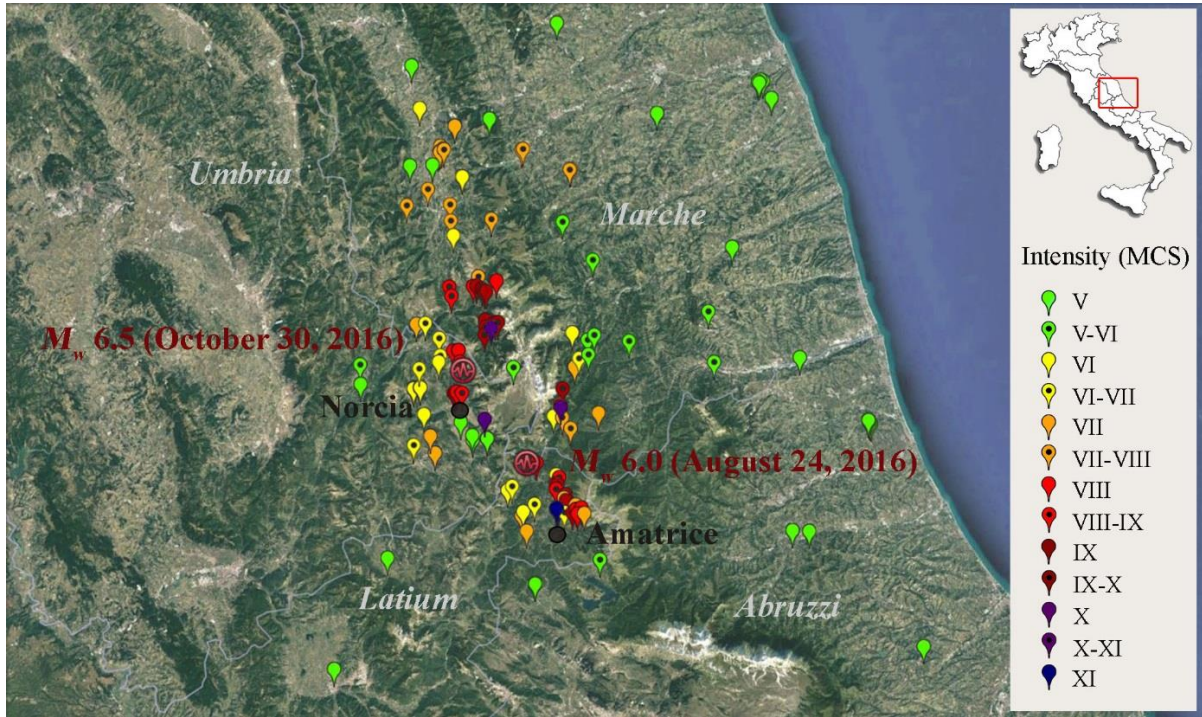


Figure 1: Locations of the 158 URM churches pertaining to the four regional boundaries, along with the epicentres of the main seismic events

Generally, when the interpretation of observed damage is of interest, a macroseismic intensity is used [9,10] because it is directly assigned to stricken locations on the basis of the occurred effects on the built and natural environment. Consequently, Mercalli-Cancani-Sieberg (MCS) macroseismic intensity (Figure 1) is considered as intensity measure in this study. Local values of MCS intensity [11,12] are attributed to each church location using a triangulation-based linear 2-D interpolation when macroseismic intensity was not available for the settlement of interest. Either one of the two main earthquakes of the sequence, the August 24, 2016 (M_w 6.0) or the October 30, 2016 (M_w 6.5) shock is used as reference event, depending on the location of the church and the following date of survey. Therefore, the damage of 49 churches out of 158 is referred to the August 24 shock, and that of 109 churches to the October 30 shock. The majority of churches experienced a macroseismic intensity equal to V (20%), VII-VIII (15%) and VIII-IX (13%). The remaining churches' distribution decreases with MCS intensities, ranging between V-VI (10%), and XI (2%).

2 LOCAL DAMAGE ASSESSMENT

The assessment of the damage occurred to the Central Italy churches was carried out by assigning six levels of damage, ranging between 0 (no damage) and 5 (total collapse), to each possible collapse mechanism in Table 1 following the qualitative expert judgment approach of the European Macroseismic Scale [13]. The percentage of mechanisms whose activation was identified is presented in Figure 2, in conjunction with the percentage of the possible mechanisms. Some of the 28 mechanisms in Table 1 were rarely observed in the analysed stock because they are related to macro-elements that were seldom present. Nevertheless, some of

them (#9, #11) showed systematic activation (above 80% in the buildings where possible) although their macro-elements (vaults in the aisles, transept) were present in few buildings. Because of their rather poor sample size, these mechanisms, together with #10, 12, 15, 20, 24, are not further discussed in the following, reducing the number of accounted mechanisms to twenty-one.

As already pointed out in Marotta et al. 2017 [14], the seismic vulnerability of URM churches is strongly modified by structural details that can improve the seismic performance, (such as connections between walls and to horizontal structures, buttresses, tie rods, top beams, lateral restraint, lintels, braced roof pitch), or worsen the seismic performance (such as poor masonry quality, asymmetry conditions, thrusting elements, large slenderness, large openings, heterogeneous materials, vertical-stacked-bond vaults, lunettes). For this reason, the presence and effectiveness of the aforementioned fifteen vulnerability modifiers (Table 2) were also recorded during the investigation, and the influence of each of them on the damage of single mechanism was addressed in a disaggregated fashion, following the approach in Marotta et al. 2018 [15] originally proposed for URM churches damaged by the 2010-2011 Canterbury, New Zealand, seismic sequence.

The vulnerability of each analysed mechanism is evaluated by using multi-linear regressions, in which the response, d , representing the observed damage, and the considered explanatory variables are fitted by a linear formulation, according to:

$$d = m_0 I + m_1 x_1 + m_2 x_2 \dots + m_v x_v + b + \varepsilon \quad (1)$$

where I represents the MCS intensity measure univocally assigned to each church location and referred to one of the two main shocks; x_1, x_2, \dots, x_v are the vulnerability modifiers considered for each mechanism; $m_0, m_1, m_2, \dots, m_v$ are the obtained regression coefficients; b is the intercept and ε is the error term.

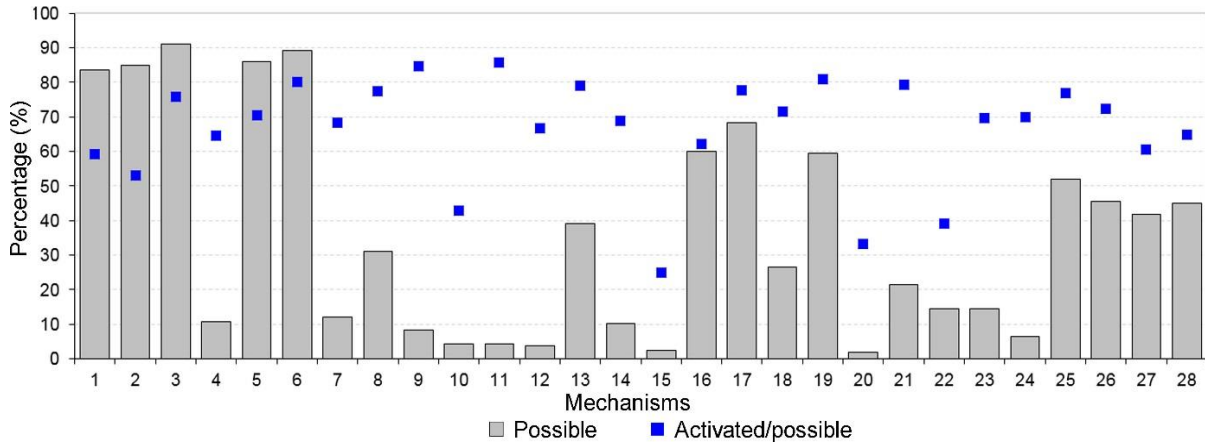


Figure 2: Percentages of possible (over the sample of 158 churches) and activated (over the sample of possible) mechanisms mentioned in Table 1

Table 2: List of the vulnerability modifiers, x_v , used in the multi-linear regression models

Ref. no.	Description
x_1	Tie rods
x_2	Lateral restraint
x_3	Buttresses
x_4	Lintels
x_5	Thrusting elements
x_6	Large openings
x_7	Top beam
x_8	Heterogeneous materials
x_9	Connections
x_{10}	Braced roof pitch
x_{11}	Slenderness
x_{12}	Asymmetry conditions
x_{13}	Poor masonry quality
x_{14}	Vertical-stacked-bond vaults
x_{15}	Lunettes

The influence of each vulnerability modifier is considered assigning it a score as indicator of either the absence or presence of a characteristic and its effectiveness. The scores range between -1 and 0 as for the structural details that are expected to improve the seismic performance, or between 0 and 1 as for the structural details that are expected to aggravate the seismic performance. Consequently, a modifier reducing the vulnerability, such as an earthquake-resistant element, will score close to -1 if effective and 0 if ineffective or absent. On the contrary, a modifier increasing the vulnerability will score close to 1 if present and 0 if absent or negligible. The effectiveness of an earthquake-resistant element and the incidence of a vulnerability increaser are entrusted to an expert judgment.

Two statistical procedures, namely Stepwise and Best Subsets [16], were used to determine the variables that generate the most efficient predictive model: the Stepwise selection method, which consists in inserting variables in turn until the regression equation involves a p -value below a selected threshold, and the Best Subsets procedure, which selects the subset of parameters that optimises an objective criterion, such as having the largest coefficient of determination. Since the coefficient of determination, R^2 , automatically increases when numerous variables are considered, for multiple-linear regressions the best regression model is identified by means of the adjusted coefficient of determination, R^2_{adj} :

$$R^2_{adj} = 1 - \left[(1 - R^2) \frac{n - 1}{n - (v + 1)} \right] \quad (2)$$

where n is the sample size of churches and $v + 1$ is the number of considered explanatory variables, including the MCS intensity measure.

Differently from a generic multi-linear regression model, the two procedures used allow to identify those parameters that can be neglected, while providing both a better damage prediction and the possibility of a faster territorial-scale vulnerability assessment [17].

For the twenty-one mechanisms considered, the coefficients defining the selected multiple-linear regressions of Eq. (1) are presented in Table 3.

Table 3: Computed coefficients of the selected regression models according to Eq. (1) for MCS as intensity measure

	Variable								
	I	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
Mech. No.	1	0.203							
	2	0.392	0.384			0.958	0.757	-1.023	
	3	0.193							1.172
	4	0.788				0.731	2.245		
	5	0.395		0.590					1.163
	6	0.240						0.487	1.485
	7	0.228				0.513			1.600
	8	0.136					1.843	0.837	2.724
	13	0.239	0.323						0.730
	14	0.325							
	16	0.175	0.482	0.540	1.136				
	17	0.268							
	18	0.142							2.156
	19	0.429	0.610			0.738			1.280
	21	0.509							
	22	0.191	0.575	0.847			1.554		
	23	0.342				0.708			
	25	0.424		0.851	1.015			1.250	1.001
	26	0.219					0.820		
	27	0.197	0.314	0.487	1.184	0.565			
	28	0.545	0.552						1.983

	Variable							
	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	b
Mech. No.	1	2.211		0.577		1.877		1.213
	2	1.987		0.638		2.314		-2.610
	3	1.306				2.039		0.931
	4					2.941		-5.974
	5	0.681		0.577		1.085	1.801	-1.037
	6	0.714		0.334		1.333	1.952	0.052
	7			0.732		2.226		-3.074
	8			0.936		2.349	-0.435	0.194
	13	1.357			1.605	1.450		1.010
	14			2.388				-0.880
	16	1.636		1.456		1.416		0.998
	17	1.316				1.409		0.822
	18					1.784	1.481	-0.008
	19	1.484	0.786			1.423		-0.292
	21	1.180				1.341		-1.581
	22					1.828		-0.444
	23				1.236	1.649		-1.387
	25	1.123		1.154		0.887		-0.412
	26			1.048	0.898	2.447		-0.731
	27	1.976		0.792	1.045	2.275		1.932
	28			1.885	3.425	1.606		-2.293

Although not included in the current Italian form, poor masonry quality was found to be crucial for at least twenty mechanisms. It is also important to highlight that the presence of poor masonry can lead to wall fragmentation (example in Figure 3a), before a rigid-body mechanism can be triggered. In the case at hand, this phenomenon was observed in 21% of the activated mechanisms. Therefore, masonry performance is confirmed to be crucial and the investigation of its mortar is highly recommended [18]. Other very relevant modifiers are connections, between intersecting walls (example in Figure 3b) or between walls and horizontal structures, which influence twelve mechanisms. On the contrary, despite it is widely known that tie rods help to reduce wall overturning [19,20], they seem to play a negligible role, probably due to the predominance of other modifiers such as connections. Similarly, buttresses only slightly influenced the predicted damage, but their presence was detected only in about 15% of the investigated churches. Large slenderness noticeably influenced the two mechanisms associated with the presence of dome and belfry (#14 and #28).



Figure 3: a) Example of poor quality masonry causing wall disintegration: Santa Maria Assunta (Torrita, Amatrice); b) Example of the relevance of connections: San Lorenzo (San Lorenzo e Flaviano, Amatrice)



Figure 4: Examples of reed-mat vaults: a) Santa Chiara (Camerino); b) Santa Maria in Via (Camerino), released from the Corps of Firefighters (www.vigilifuoco.it)

Other parameters, such as large openings (whose combined length exceeds 1/3 of the wall length), heterogeneous materials (assigned in case of reed-mat vaults, Figure 4, for mechanism #8 and when two adjacent structural elements are made of different masonry types), asymmetry conditions (e.g., due to eccentricity of a projection with respect to the underlying masonry, or due to juxtaposition of a new extension) and the presence of vertical-stacked-bond vaults, are relevant for specific mechanisms. Negative values of the coefficients are obtained in two cases, since related to vulnerability modifiers rarely present in the relative mechanisms and will require further investigation.

3 GLOBAL DAMAGE INDEX

In buildings where multiple local collapse mechanisms take place, it is important to define a synthetic index expressing the overall severity of damage. Commonly, a normalized average, i_d , proposed by Lagomarsino et al. [6], and computed as the mean of the damage scores, d_k , assigned to each of the N mechanisms that might have been activated in the church (twenty-one at most in the present case), weighted by the coefficients ρ_k , is used:

$$i_d = \frac{1}{5} \frac{\sum_{k=1}^N \rho_k d_k}{\sum_{k=1}^N \rho_k} \quad (3)$$

where the factor 1/5 normalizes i_d in the range [0,1].

The normalized average, i_d , can be transformed into a discrete variable, varying from 0 to 5, using the correlation suggested by Lagomarsino and Podestà [21]. In order to overcome a conventional estimation of the ρ_k weights, an alternative synthetic damage index has been proposed in Marotta et al. [15]. Re-expressing in vector form Eq. (1), it follows:

$$\mathbf{d} = \mathbf{m}_0 I + \mathbf{c} + \mathbf{b} + \boldsymbol{\varepsilon} \quad (4)$$

where \mathbf{d} represents the vector of observed damage, \mathbf{m}_0 is the vector of the regression coefficients of the intensity measure I , vector \mathbf{c} groups the regression modifiers associated with the twenty-one mechanisms (e.g., for the j -th mechanism: $c_j = m_{j1}x_{j1} + m_{j2}x_{j2} \dots + m_{jv}x_{jv}$), \mathbf{b} is the vector of intercepts and $\boldsymbol{\varepsilon}$ is the vector of error terms. The ground motion parameter I that best fits the observed damage can be obtained by minimizing the sum of squares of the error terms:

$$I = \frac{\mathbf{m}_0^T (\mathbf{d} - \mathbf{b} - \mathbf{c})}{\mathbf{m}_0^T \mathbf{m}_0} = \frac{\mathbf{m}_0^T (\mathbf{d} - \mathbf{b})}{\mathbf{m}_0^T \mathbf{m}_0} - \frac{\mathbf{m}_0^T \mathbf{c}}{\mathbf{m}_0^T \mathbf{m}_0} \quad (5)$$

The ground motion parameter x_1 is equal to the difference of two terms, where the first depends on observed damage (including intercepts) and can be considered as a damage index, D_s :

$$D_s = \frac{\mathbf{m}_0^T (\mathbf{d} - \mathbf{b})}{\mathbf{m}_0^T \mathbf{m}_0} \quad (6)$$

The second term depends on the vulnerability modifiers alone, and can be considered as a vulnerability index, V :

$$V = \frac{\mathbf{m}_0^T \mathbf{c}}{\mathbf{m}_0^T \mathbf{m}_0} \quad (7)$$

Accordingly, Eq. (5) can be rewritten as:

$$I = D_s - V \quad (8)$$

A simple additive model is therefore established, where the ground motion parameter, I , is computed as the difference between the synthetic damage index, D_s , and the vulnerability index, V , and all quantities share the same unit of measure. The synthetic damage index of Eq. (6) is an *observed* damage, which can be used for comparisons and model validation. A comparison of the *observed* synthetic damage index with the normalised average i_d , computed for Central Italy churches according to Eq. (3) assuming $\rho_k = 1$, is provided in Figure 5a, and a good correlation is achieved, confirming the efficacy of the proposed index.

As Eq. (8) establishes a relationship between three quantities, once damage and vulnerability are known (e.g. after an earthquake) it is possible to estimate the ground motion severity, gaining a quantitative alternative to the conventional macroseismic intensity, which enables an estimate of ground motion severity on a specific class of buildings accounting for their vulnerability. The limited correlation (Figure 5b) between the MCS intensity assigned after the seismic sequence and the ground motion parameter, I , obtained with Eq. (8) depends on the different stock of buildings considered for their computation, in the case of x_1 solely churches, whereas all constructions for the attribution of MCS intensity (in the case at hand mostly ordinary unreinforced masonry buildings).

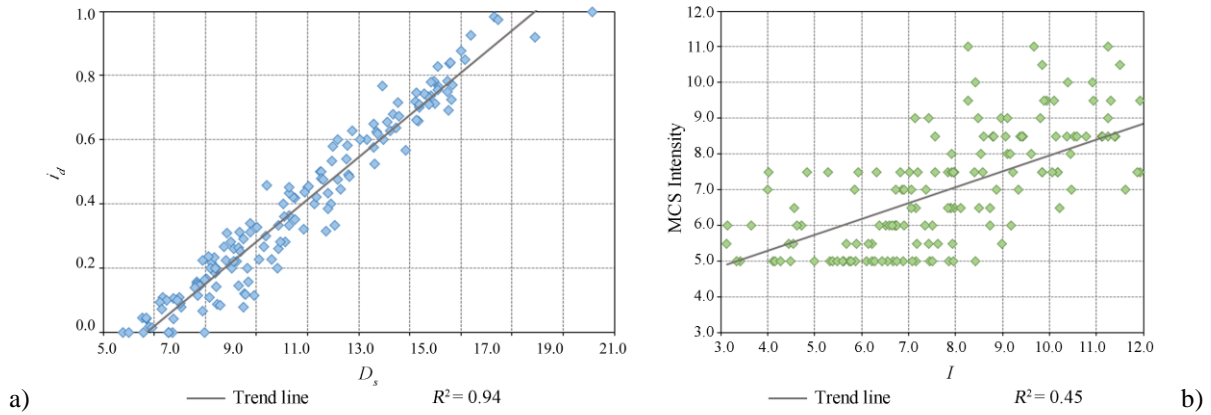


Figure 5: a) Correlation between normalised average, i_d , computed for Central Italy churches following Eq. (3) and *observed* synthetic damage index, D_s , obtained with Eq. (6); b) Comparison between assigned MCS intensities and ground motion parameter, I , computed following Eq. (8)

On the other hand, when the expected ground motion and vulnerability are provided (e.g. in a risk analysis), the expected damage can be forecasted as follows:

$$D_s = I + V \quad (9)$$

Considering the long timespan covered by Italian macroseismic catalogues [22], law of occurrence and expected intensities can be estimated for most places. Therefore, the coefficients in Table 3 can be used in future preventive assessments, as done by Marotta et al. [15], wherein a worked out example is shown.

4 CONCLUSIONS

The 2016–2017 Central Italy earthquake sequence caused extensive damage to the national architectural heritage, especially to unreinforced masonry churches. The damage data collected in the aftermath of the main events for a sample of 158 religious buildings in the affected area highlighted once again the intrinsic structural vulnerability of this architectural type.

Because unreinforced masonry churches respond to earthquakes as a composition of macro-elements, observed damage was interpreted mechanism by mechanism, also accounting for differences in vulnerability besides the severity of shaking alone. Such investigation was conducted by using multiple-linear regressions, according to statistical procedures, in order to obtain the model having the largest coefficient of determination together with the smallest number of relevant modifiers for a faster territorial scale application. Accordingly, the coefficients defining the regression models of twenty-one mechanisms were computed.

Commonly, damage occurred to churches is analysed by computing a global damage index, based upon summing up and weighting separate mechanism damage levels. Herein, an alternative synthetic damage index has been identified, by minimizing the sum of squares of the difference between expected and observed damage. The proposed index has the advantage of not requiring a conventional estimation of the weights used in previous definitions of a global damage index and is exclusively based on observed data. The applied method, already calibrated on observed damage from other earthquakes affecting unreinforced masonry buildings, and herein recalibrated for the assessment of the global response of the Central Italy unreinforced masonry churches, provides good results and a good correlation when compared to a mean damage. An innovative advantage of the proposed damage index, which is a combination of a ground motion intensity measure and building vulnerability, is the possibility to highlight the specific influence to damage of each component, separating the role of ground motion severity from that of building vulnerability.

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