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Multi-linear models for the rapid assessment of the vulnerability of unreinforced masonry churches involved in the 2016-2017 Central Italy seismic sequence

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ABSTRACT

Religious buildings constitute an important part of the cultural heritage of a country, for both spiritual and cultural reasons. The seismic sequence that struck Central Italy in 2016-2017 highlighted once again the high vulnerability of unreinforced masonry churches, causing invaluable losses to the national heritage. The seismic response of 158 affected buildings is analysed following the main events of the seismic sequence, by means of the identification of the collapse mechanisms activated and the description of their structural behaviour. By using multi-linear models, regression lines are obtained in terms of mechanism and, in addition to the severity of shaking alone, the structural features that can improve or worsen the seismic response are accounted for, including repair and strengthening interventions, such as tie rods, ring beams, etc. The use of statistical models based on the collection of typological data by means of rapid evaluations implies uncertainties in the prediction of regression models. Assessments on the confidence intervals of the individual regression coefficients are carried out in order to determine the reliability of the proposed procedure.

1 INTRODUCTION

A strong seismic sequence, started on August 24 (M_w 6.0), struck Central Italy in 2016-2017, causing severe damage and hundreds of casualties over a wide area within the boundaries of Latium, Abruzzi, Umbria and Marche regions (Figure 1). The strongest event occurred on October 30, 2016 (M_w 6.5) and mostly affected the municipalities of Norcia and Castelsantangelo sul Nera. The aftermaths of such event were extremely destructive for the religious buildings in the city of Norcia, where almost all churches suffered extensive damage and collapses (Penna et al. 2018).

The building portfolio in the affected area is characterised by numerous historical constructions, which have been strongly damaged. Among them, it is widely known that churches frequently exhibit a seismic vulnerability higher than ordinary buildings (D'Ayala 2000), 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 (Sorrentino et al. 2014). As known, 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 (Giuffré 1988; Doglioni et al. 1994; Lagomarsino et al. 2004; Milani and Valente 2015; Borri et al. 2019). Accordingly, in order to correlate the damage related to each collapse mechanism against ground motion intensity and churches' specific characteristics, the observed behaviour of a sample of 158 Central Italy URM churches is herein analysed by means of statistical procedures accounting for 28 possible local collapse mechanisms (Table 1), as currently adopted in Italy for post-earthquake assessment of churches (Calderini and Lagomarsino 2010; Da Porto et al. 2012; De Matteis et al. 2014), according to DPCM (2011). Among the church sample assessed in the stricken regions, 32 were located in Latium, 41 in Umbria, 73 in Marche and 12 in Abruzzi regions.

Table 1. List of the possible 28 collapse mechanisms.

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

Generally, when dealing with observed damage interpretation, a macroseismic intensity is used (Dolce et al. 2006; Vicente et al. 2014) because it is directly assigned on the basis of effects on the built and natural environment. Consequently, Mercalli-Cancani-Sieberg (MCS) macroseismic intensity (Figure 1) is considered in this work. Local values of MCS intensity (Azzaro et al. 2016; Galli et al. 2016) 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 consequent date of survey. Hence, the damage of 49 churches out of 158 is referred to the first event, and that of the remaining 109 churches is referred to the October 30 shock. Distribution of churches according to MCS intensities, ranging between V and XI, is given in Figure 2, showing that the majority of churches experienced a macroseismic intensity equal to V (20%), VII-VIII (15%) and VIII-IX (13%).

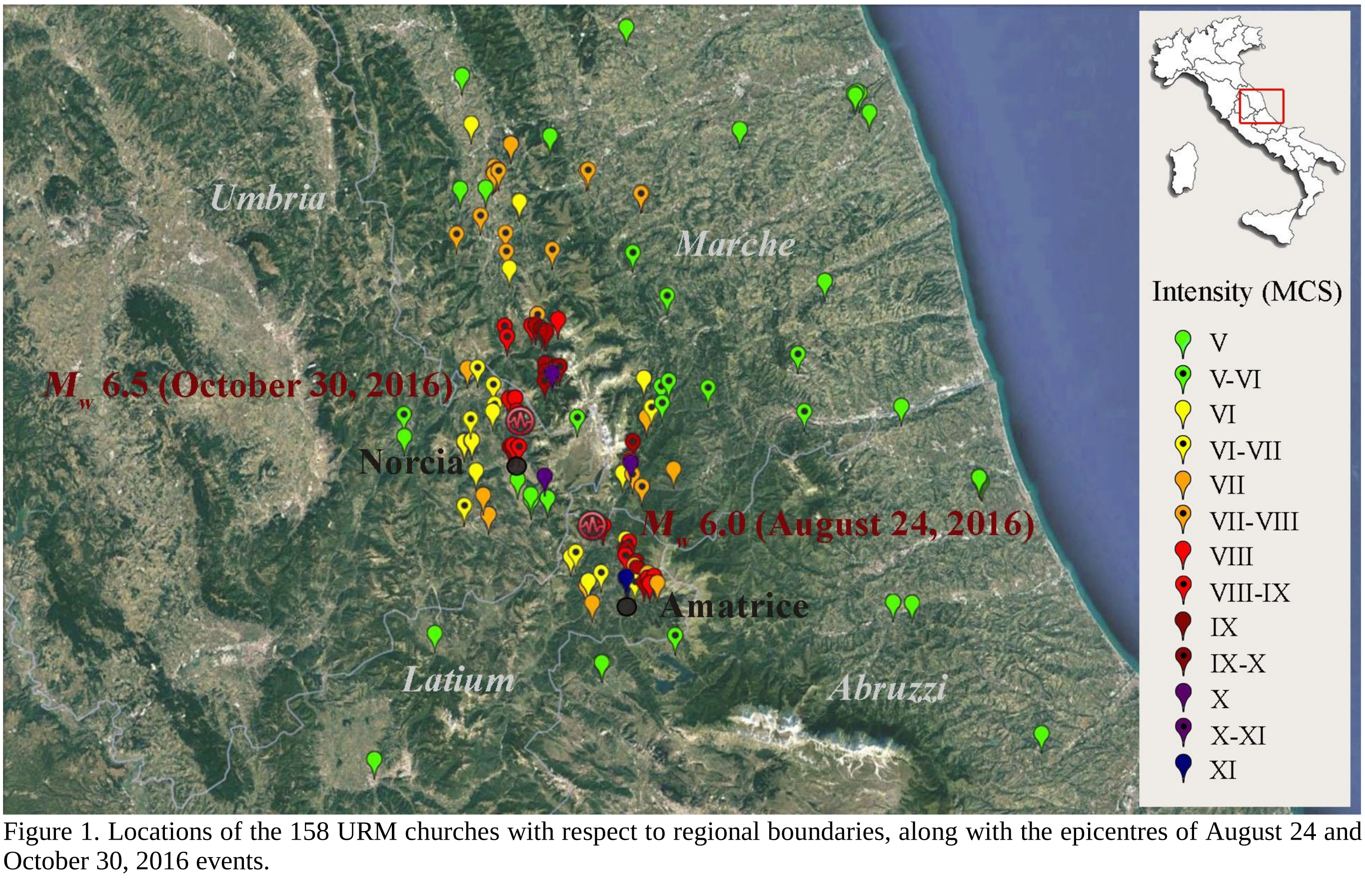

Figure 1. Locations of the 158 URM churches with respect to regional boundaries, along with the epicentres of August 24 and October 30, 2016 events.

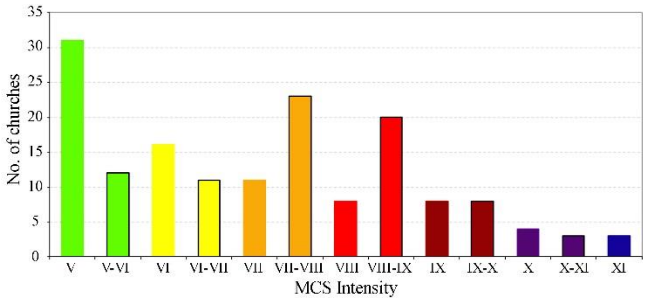

Figure 2. Number of inspected churches classified according to felt MCS intensity.

2 LOCAL DAMAGE ASSESSMENT

As previously mentioned, the earthquake response of historical URM constructions, and particularly churches, can be described by identifying separate macro-elements, which are specific architectural portions (e.g., façade, transept, apse, bell tower, vaults) whose seismic behaviour is only weakly coupled with that of adjacent parts. Accordingly, 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 following the qualitative expert judgment approach of the European Macroseismic Scale (Grünthal 1998). The percentage of mechanisms whose activation was identified is presented in Figure 3, in conjunction with the percentage of the possible mechanisms. Some mechanisms (#9, #11) showed systematic activation (above 80% in the buildings where possible) but their macro-elements (vaults in the aisles, transept) are 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.

As showed in Marotta et al. (2017), the seismic vulnerability of URM churches is strongly influenced by structural details whose presence 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 aggravate 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 different vulnerability modifiers (Table 2) have been also investigated, and their effect on the damage of each mechanism has been addressed, following the approach in Marotta et al. (2018).

The vulnerability of each analysed mechanism has been evaluated by using multi-linear regressions, in which the response, *d*, representing the occurred damage, and the considered *v* explanatory variables, *x*, accounting for the vulnerability modifiers, are fitted by a linear formulation, according to:

$$d = m_1 x_1 + m_2 x_2 + \ldots + m_v x_v + b + \varepsilon \qquad (1)$$

where x_1 represents the MCS intensity measure univocally assigned to each church location and referred to one of the two main shocks; x_2, x_3, … x_v are the vulnerability modifiers considered for each mechanism; m_1, m_2, … m_v are the obtained regression coefficients; *b* is the intercept and ϵ is the error term.

The influence of each vulnerability modifier is considered assigning them a score between 0 and 1 as indicator of either the absence or presence of a characteristic and its effectiveness. A modifier reducing the vulnerability, such as an earthquake-resistant element, will score close to 0 if effective and 1 if ineffective or absent. 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.

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

Ref. no.	Description
x_2	Tie rods
x_3	Lateral restraint
x_4	Buttresses
x_5	Lintels
x_6	Thrusting elements
x_7	Large openings
x_8	Top beam
x_9	Heterogeneous materials
x_{10}	Connections
x_{11}	Braced roof pitch
x_{12}	Slenderness
x_{13}	Asymmetry conditions
x_{14}	Poor masonry quality
x_{15}	Vertical-stacked-bond vaults
x_{16}	Lunettes

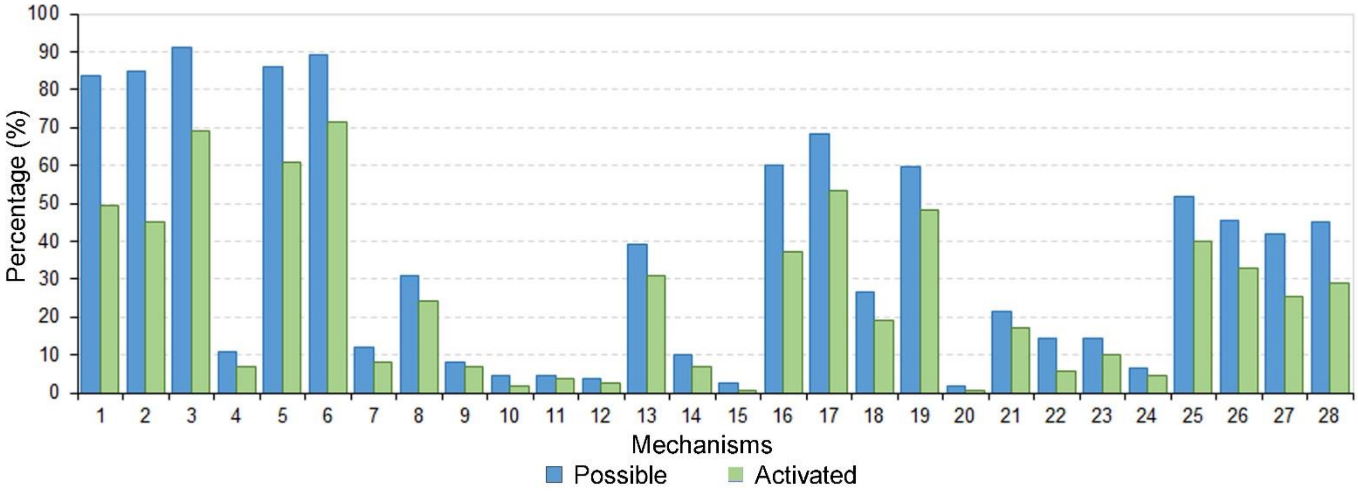

Figure 3. Percentages of possible and activated mechanisms over the sample of 158 churches.

Two statistical procedures, called Stepwise and Best Subsets (Draper and Smith 1998), were used to determine the variables that generated the most efficient predictive model: the Stepwise selection method, that consists in inserting variables in turn until the regression equation involves a *p*-value below the selected threshold, and the Best Subsets procedure, that selects the subset of parameters that optimise an objective criterion, such as having the largest coefficient of determination. Because when multiple variables are considered R^2 automatically increases, for multiple linear regressions the best regression model is identified by means of the adjusted coefficient of determination, R^2_{adj}:

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

where R^2 is the coefficient of determination, n is the sample size and v is the number of considered vulnerability modifiers.

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.

For the twenty-one mechanisms considered, the coefficients defining the selected multiple-linear regressions of Eq. (1) are presented in Table 3. Despite 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 disintegration (examples in Figure 4), before a rigid-body mechanism can be activated. In the case at hand, this phenomenon was observed in 21% of the activated mechanisms. Therefore, masonry performance is crucial and the investigation of its mortar is recommended (Liberatore et al. 2016). Other very relevant modifiers are connections, between intersecting walls or between walls and horizontal structures, which influence twelve regressions. On the contrary, despite is widely known that tie rods help to reduce the overturning of the walls (Giresini et al. 2018), they seem to play a negligible role, probably due to the predominance of other modifiers such as connections. It was also found that 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). 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 5, 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.

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

Variable **Mech. No.**	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
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 **Mech. No.**	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	b
1	2.211		0.577		1.877			-1.113
2	1.987		0.638		2.314			-1.655
3	1.306				2.039			-0.410
4					2.941			-5.974
5	0.681		0.577		1.085	1.801		-2.316
6	0.714		0.334		1.333	1.952		-1.119
7			0.732		2.226			-1.166
8			0.936		2.349		-0.435	-0.674
13	1.357			1.605	1.450			-0.784
14			2.388					0.269
16	1.636		1.456		1.416			-2.433
17	1.316				1.409			-0.639
18					1.784		1.481	-0.008
19	1.484	0.786			1.423			-3.294
21	1.180				1.341			-2.642
22					1.828			-1.906
23				1.236	1.649			-1.387
25	1.123		1.154		0.887			-3.497
26			1.048	0.898	2.447			-0.731
27	1.976		0.792	1.045	2.275			-2.313
28			1.885	3.425	1.606			-2.822

Figure 4. Example of poor quality masonry causing wall disintegration: San Lorenzo Martire (Cossito, Amatrice)

Figure 5. Examples of reed-mat vaults: a) Santa Chiara (Camerino).

3 UNCERTAINTIES OF REGRESSION MODELS

The use of statistical models based on the collection of typological data implies uncertainties in the predictions of the regressions. In order to assess the reliability of the proposed procedures, an investigation of the confidence intervals of the observed damage and of individual regression coefficients is carried out.

In fact, a confidence interval is an interval estimate of the *mean value* computed from the statistics of the observed data, and its width provides an idea of uncertainty about its estimation. It has an associated confidence level that quantifies the level of confidence that the mean value lies in such interval. The confidence level is usually chosen equal to 0.05, meaning that there is a 95% probability that the *linear regression line* of the population will lie within the confidence interval computed from the sample data (Ross 2004). Accordingly, the lower the confidence level specified, the larger the estimated range that is likely to contain the line.

Regression lines of the observed damage for two of the twenty-one considered mechanisms are shown in Figure 6 together with confidence intervals and, for comparison reasons, prediction bounds.

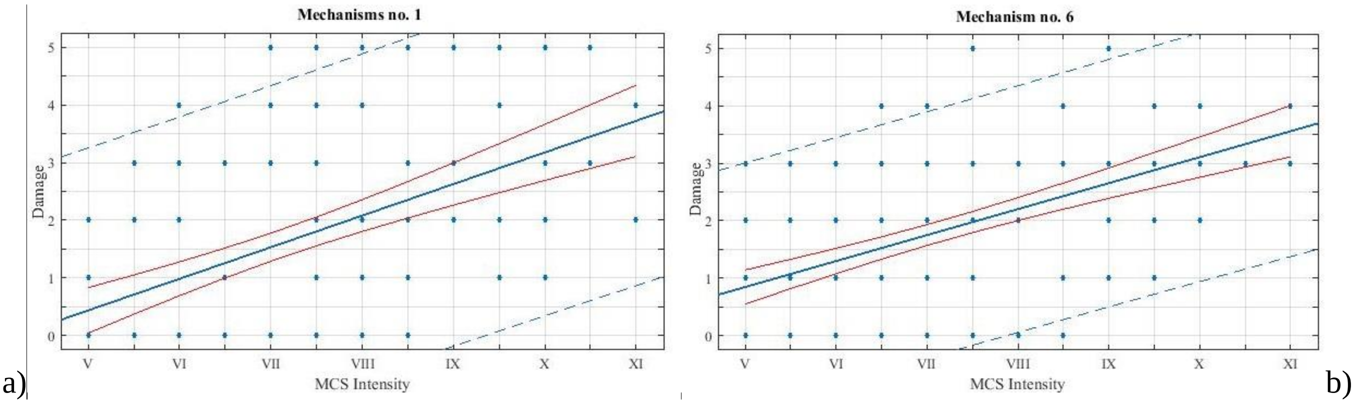

Figure 6. Regression lines of the observed damage with scatter plot of the data with confidence (in red) and prediction (in dashed blue) intervals for: a) mechanism no. 1; b) mechanism no. 6.

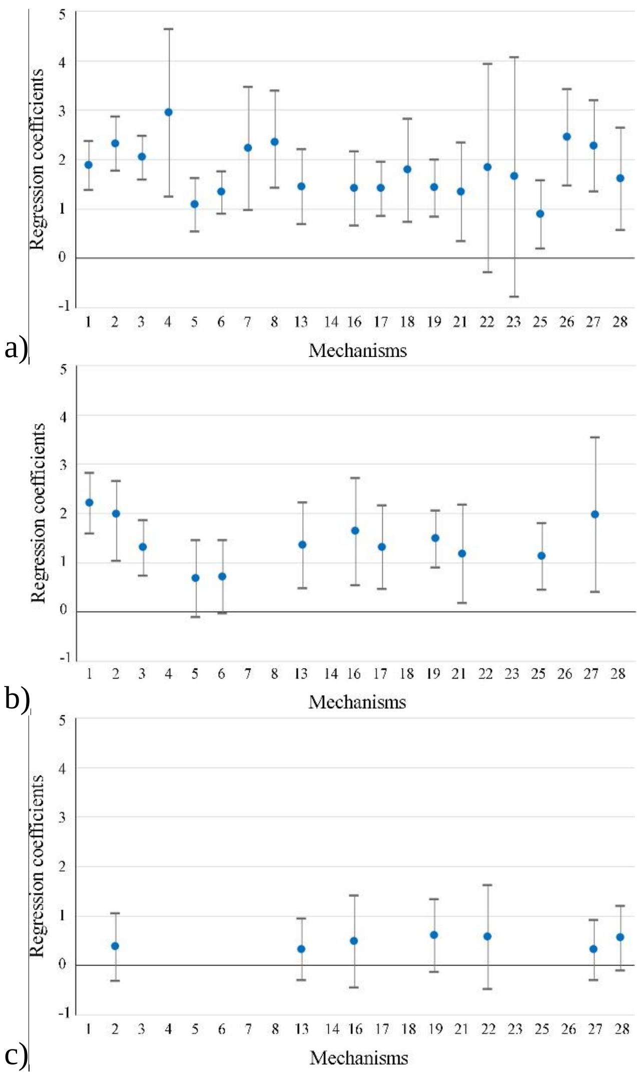

Figure 7. Boxplot of confidence intervals of specific vulnerability modifiers for each considered mechanism: a) poor masonry quality; b) connections; c) tie rods.

The prediction bounds provide information on *individual* predictions of the accounted dependent variable, giving a range of values around which an additional observation of the variable can be expected to be located. In fact, prediction intervals provide a range of values where we can expect future observations to fall and are useful when the aim is using the model to predict individual values of the response. As shown in Figure 6, the confidence interval is associated to a smaller range of values, because it is an interval estimate for an average value rather than an interval estimate for a single observation, as provided by the prediction intervals. This result confirm the recommendation of using territorial scale analyses only for average estimation rather than individual forecasts.

The confidence intervals of each regression coefficient have been computed, in addition to the mean estimate, to investigate the expected range of dependent variables value. In Figure 7a-b, the confidence limits of the two vulnerability modifiers, poor masonry quality and connections, found to be crucial for most mechanisms in §2 are presented, showing acceptable limit intervals, with few mechanisms presenting large intervals due to specific conditions of the sample size. Even the vulnerability modifiers discarded by the statistical procedure for some of the accounted mechanisms show reasonable confidence intervals (Figure 7c), confirming the reliability of the proposed regression models.

4 CONCLUSIONS

The 2016–2017 Central Italy earthquake sequence caused extensive damage to the national architectural heritage, with particular reference to unreinforced masonry churches. The damage data collected 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, as typical in literature. Such investigation was conducted by using multiple-linear regressions, according to Stepwise and Best Subsets 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.

Because the use of statistical models based on the collection of a limited set of typological data implies uncertainties in the prediction of regression models, an assessment of the confidence intervals of the observed damage and on individual regression coefficients obtained by the regressions was carried out in order to determine the reliability of the proposed procedure. Comparing the outcomes of some of the coefficients related to the additional vulnerability modifiers considered in the regression models, it is proved that there are reasonably small intervals, thus confirming the consistency of the proposed regression models that allow expeditious evaluations of the vulnerability of religious buildings following earthquakes.

However, confidence intervals are much smaller than prediction intervals, recommending the use of such territorial-scale models only for average estimation rather than for individual assessment.

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