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Dynamic Models for the Seismic Analysis of Ancient Bell Towers

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ABSTRACT: The post-seismic damage assessment of slender structures has highlighted the difficulty to foresee their structural response. The observed damage of this kind of buildings are different although the constructive and typological details are, often, very similar. The bell-tower analysis is meaningful in Italy for the high number of ancient religious buildings. In order to evaluate the seismic response of this kind of structures, in this paper the bell-towers have been simulated by two sub-structures (tower and belfry). Dynamic analyses have been carried out and the amplification effect at the base of the belfry has been evaluated in spectral quantities. At the same time a statistical analysis of the available data surveyed after the recent Italian seismic events has been carried out, defining, therefore, the vulnerability curves of the two different macroelements (tower and belfry). This approach has allowed us to highlight the fundamental rule of the dynamic characteristics of the structure and of the seismic input, confirming, in a qualitative way, the results obtained by the dynamic numerical analyses.

1 INTRODUCTION

Ancient slender masonry structures may be traced to different structural typologies: lookout towers, bell towers, chimney stacks, minarets, etc. At the time of historical seismic events such constructions, even though intended for different functions and belonging to different epochs and architectural styles, have shown a structural response that was difficult to foresee in advance. Observation of post-earthquake damage has indeed led to the finding of many collapse modes when faced with the same typological features and, in some cases, an unexpected resistance if compared with their intrinsic vulnerability.

The high number of bell towers present on Italian soil brings the problem of seismic analysis of this typology to the foreground.

Systematic observation of seismic damage has pointed out how the belfry represents, above all at the time of high-magnitude earthquakes, the most vulnerable element. The structural behaviour of this structure, though it may be intuitively traced back to the typological vulnerability of the macroelement (slenderness of the piers, summit masses, horizontal static thrusts, etc.), cannot disregard the seismic input that solicits it. Indeed, it is strongly modified compared to the accelerogram acting at the base of the tower due to the filtering effect of the entire structure. To be able to understand how much this aspect influences the belfry's response, firstly a series of dynamic analyses were conducted (finite element code ANSYS 8.0) using a matching Eurocode 8 response spectrum (EC8) of certain real bell towers. This analysis led to attainment of a preliminary assessment of the variation of the seismic input directly in spectral terms, highlighting the importance of amplification phenomena in assessment of the seismic response of belfries.

At the same time a statistical analysis was carried out on the data gathered following the major Italian earthquakes, with reference to the tower and belfry macroelements. This research, besides supplying useful information about the typological and structural vulnerability of these structures, allowed confirmation, even though qualitatively, of the numeric results.

2 ASSESSMENT OF THE SEISMIC INPUT OF A BELL TOWER

From the analysis of the post-earthquake damage to bell towers it came out how often the belfry, despite showing different damage typologies and collapse mechanisms, is an element characterized by high vulnerability within the structure. Part of this vulnerability may be associated with the summit position of this macroelement. Indeed, it is affected by the filtering effect of the structure that can generate, at the height of the belfry impost, substantial variations of content as a frequency of the ground level input. In order to seize on the relevance of this aspect, different dynamic elastic analyses of actual bell towers were carried out, of which are shown, to be brief the results of the bell tower of the church of S. Cassiano in San Casciano dei Bagni (Siena) deemed representative for its shape and dimensions of the typology under scrutiny (Casolo 1996, Casolo 1998, Casolo 2001). The bell tower has a square plan with dimensions of the base section equal to 5.30 m and a total height of about 27.4 m. The modelling of the bell tower was carried out using a simplified schematization, containing beam elements (BEAM4) having six degrees of freedom per node. To this end the bell tower was subdivided into seven sectors with constant geometric and elastic characteristics, in such way as to associate beam-elements having the same characteristics for each sector.

The axial and shear elastic modulus (*E* and *G*) were assumed as constant throughout the bell tower, respectively equal to 1050 N/mm^2 and 175 N/mm^2.

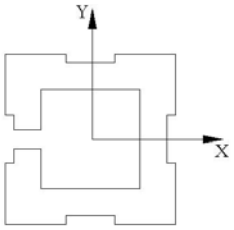

Figure 1 : reference system adopted for the sectors.

Table 1 : Geometric features of each sector

	Area m^2	Height m	Moment of inertia x axis m^4	Moment of inertia y axis m^4	Moment of torsional inertia m^4
Sector 1	18.3	2.2	61.3	50.7	72.2
Sector 2	21.1	5.2	61.6	61.6	83.5
Sector 3	20.3	1.2	61.6	58.3	80.4
Sector 4	19.1	3.2	60.9	53.3	73.7
Sector 5	16.0	6.3	50.5	48.6	66.1
Sector 6	12.3	4.9	39.7	39.7	54.4
Sector 7	8.1	4.4	28.5	28.5	36.23

The presence of ceilings, vaults or concentrated masses (i.e. bells), was modelled by introducing at the level of each floor, some additional masses (MASS21). This model, considered perfectly embedded at the base, allowed assessment, through a modal analysis, of the periods of vibration and the associated modal forms.

Table 2 : Vibration periods and modes

Mode	Period (s)	Predominant vibration direction
1	0.9427	x – first mode
2	0.9110	y – first mode
3	0.3824	Torsional
4	0.2306	x – second mode
5	0.2283	y – second mode
6	0.1404	Torsional

Later a dynamic elastic analysis was carried out, using a matching Eurocode 8 response spectrum (EC8), applied in the direction of the first mode and requiring in output the nodal displacements at the summit height of each sector into which the structure was subdivided. Knowledge of the time-history of displacement and consequently relative acceleration allowed attainment of the temporal histories of the absolute accelerations at the height of each sector, adding them to the input accelerogram.

Definition of the elastic response spectrum associated with each accelerogram highlighted the filtering effect of the structure directly in spectral terms. In Fig. 2 the elastic response spectrums obtained in correspondence with each sector are shown, starting from the one placed at the lowest height. It is pointed out how the spectrum at the height of sector 6 is representative of the input that acts at the base of the belfry.

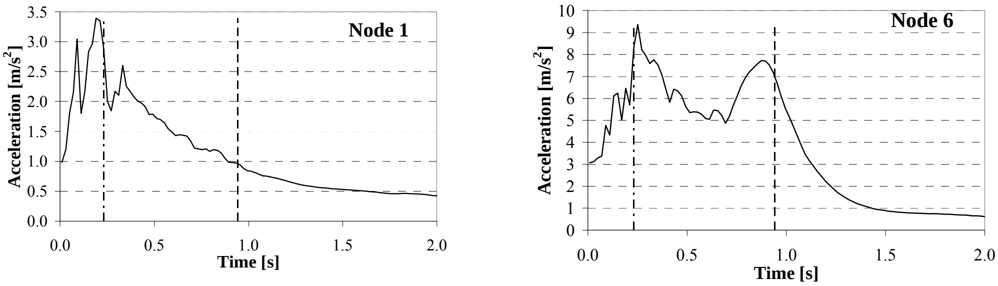

Figure 2 : Response spectrums at the base of the tower and belfry.

From the analysis of the results obtained, it comes out how the spectrums at different heights show considerable amplifications compared to the spectrum associated with the input accelerogram (Fig. 3). Furthermore, they show peaks in correspondence with the periods associated with the first and second modal form (1st and 4th period, shown respectively in Figure 2 with a dotted line and dash and dot). This aspect highlights the importance that periods higher than the first have in seismic analysis of slender structures, such as bell towers. Such structures, indeed, by virtue of their slenderness, may present periods higher than the first with frequencies that still fall within the harmonic content of the forcing vibration and, therefore, not negligible. Indeed, in the case in question, if the period associated with the second modal form is superimposed on the elastic spectrum of the input accelerogram (Fig. 3), it can be seen how this falls in the stretch of maximum amplification of the spectrum (plateau) and cannot, therefore, be overlooked. Analysing the entity of the peaks of the different spectrums, it can also be seen how the amplification is correlated to the same modal form. Fig. 4 shows the entity of the anchorage acceleration of the spectrums relative to the different heights and amplification of both peaks compared to the maximum acceleration at ground level as a function of the height normalized to the height of the bell tower. From an analysis of the graph it is possible to see how the value of the peak placed in correspondence with the first mode has a monotonous growing trend, while that placed in correspondence with the period relative to the second modal form shows a bending in correspondence with the height at which there is the node of the modal form itself.

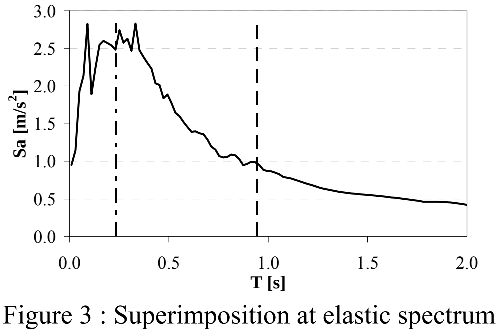

Figure 3 : Superimposition at elastic spectrum of the input accelerogram with the first and fourth mode of the structure

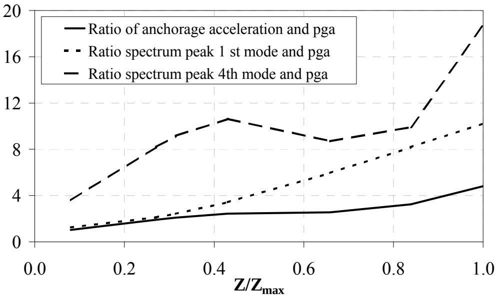

Figure 4 : Trend of the anchorage and peak accelerations compared to pga of the input accelerogram as a function of different heights

From a comparison of the elastic spectrum associated with the input accelerogram with those obtained at different heights and from the analysis of the entities of the amplifications present it can be stated how the aspect of filtering action of the structure plays a fundamental role in the comparisons of seismic analysis of the belfry.

3 VULNERABILITY ANALYSIS FOR THE BELL TOWER AND BELFRY MACRO-ELEMENTS

In order to obtain a direct comparison of the seismic behaviour of bell towers, a statistical analysis was performed on the data relative to the census campaigns carried out following the major Italian earthquakes. Re-elaboration of the data relative to bell tower and belfry macroelements allowed attainment of information surveyed directly and useful indications of the seismic behaviour of such structures, showing the soundness of the numeric results from a purely statistical point of view.

Assessment of seismic behaviour through definition of damage probability matrices (DPM) and vulnerability curves, indeed, allows attainment of an overall framework of the seismic behaviour of a structural typology or a substructure, at the same time identifying the vulnerability indicators and the anti-seismic defences.

3.1 Vulnerability curve for bell tower and belfry macroelements

Under the scope of a macroseismic approach, the survey campaign for damage and seismic vulnerability, carried out following the 1997 earthquake in Umbria and the Marches, led to definition of vulnerability curves for churches (Lagomarsino and Podestà 2004b) able to correlate the damage to the macroseismic intensity as a function of the vulnerability of the church:

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I + 3.4375 \cdot i_v - 8.9125}{\beta}\right)\right] \quad (1)$$

where μ_D is the mean damage grade depending on the parameter i_v (vulnerability score), directly obtainable from the survey form (Lagomarsino and Podestà 2004a) and β (equal to 3 for churches) is connected to the function slope and represents a ductility factor.

This function is analogous to the one proposed by Sandi (1994) and that has been used by Giovinazzi and Lagomarsino (2003) for ordinary buildings:

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I + 6.25 \cdot V_I - 13.1}{2.3}\right)\right] \quad (2)$$

where the parameter V_I is a vulnerability index, defined for ordinary buildings and ranging from 0 to 1, following the vulnerability classification in EMS-98 (Grunthal et al. 1998). Therefore, it is possible to use the same general expression, through the transformation of the vulnerability score i_v into the vulnerability index V_I, by the following linear relation:

$$V_I = 0.67 + 0.55 i_V \quad (3)$$

In this paper, on the basis of the data available, a definition of the vulnerability curves for the bell tower and belfry is proposed, using the very same function of interpolation used for churches and ordinary buildings. To this end the information gathered following the earthquakes in Friuli (1976), Umbria and the Marches (1997), Molise (2002) and Lombardy (2004), have been standardized to the criteria adopted by the European macroseismic scale (EMS-98, Gruntal et al. 1998). The information used has been taken, for the seismic events in Umbria and the Marches, Molise and Lombardy, from the damage survey and church vulnerability forms, while for what concerns the data for Friuli, the information available in the book "*Le chiese e il terremoto* (Churches and the earthquake)"- (Doglioni, *et al.,* 1994) and from the "*Catalogo dei forti terremoti* (Catalogue of strong earthquakes)" - (Boschi et al. 1997) was used. The willingness to computate in the analysis the data relative to the Friuli earthquake, stems from the need to have indications about behaviour at the time of seismic events of high intensity.

Definition of the vulnerability curves was initially carried out considering each seismic event individually, therefore assessing the representative parameters of the curve (V_i and β) only in the range of macroseismic intensity that characterized each event. This approach led to the identification of a set of vulnerability curves, defined solely on the macroseismic intensities effectively recorded, consenting their overall assessment through the tangle of the different traits

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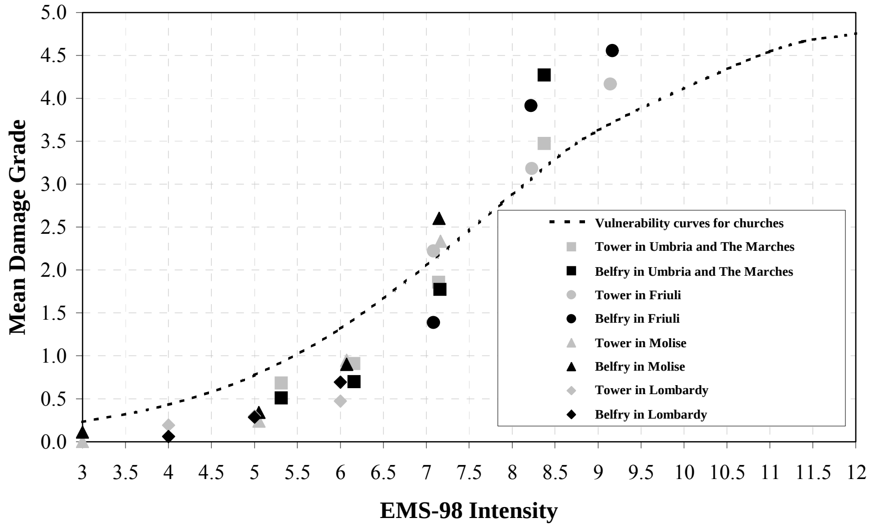

Figure 5 : Mean damage grade of belfries and bell towers

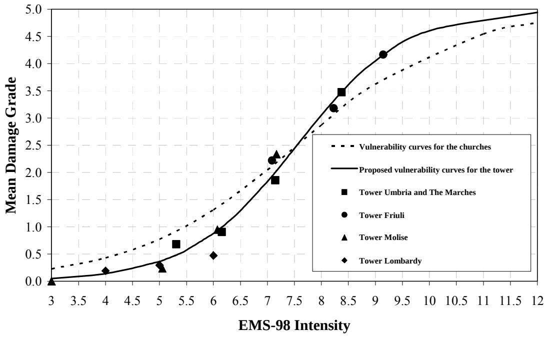

Figure 6 : Vulnerability curve of bell towers

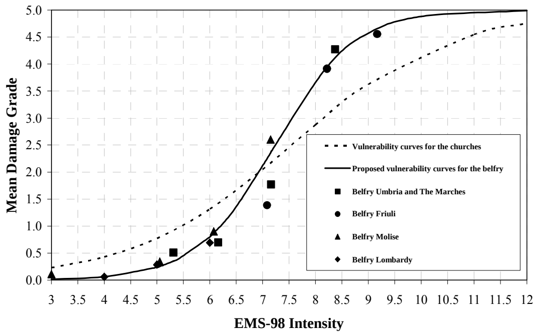

Figure 7 : Vulnerability curve of belfries

Table 3 : Vulnerability curve parameters for belfries and bell towers

Macroelement	V_I	β
Tower	0.89	2
Belfry	0.94	1.49

If one compares the vulnerability curves proposed for the bell tower and belfry with that representative of churches, one sees how the initial trend of the curves obtained for bell towers and belfries show a lower level of damage compared to churches, while for seismic events of such intensity as to generate an appreciable damage level (average damage level equal to 2), both the bell tower and belfry macroelements result more vulnerable compared to the behaviour expected for churches.

It can be seen how the vulnerability curve for bell towers presents the same vulnerability index V_I as churches but a lower value of the ductility factor β. As far as belfries are concerned, the vulnerability curve shows an increase of the vulnerability index V_I compared to that for churches and a greater decrease of the ductility index β. This aspect is confirmed by observation of the damage surveyed following the major Italian earthquakes: the damage mechanisms that are found are connected to the cracking states that separate the belfry into parts, causing in a fragile way total or partial collapse due to loss of equilibrium. Observing the damage probability matrices relative to both macroelements one can notice how the damage distributions show bipolar trends for the belfry macroelement (Figs. 8-12).

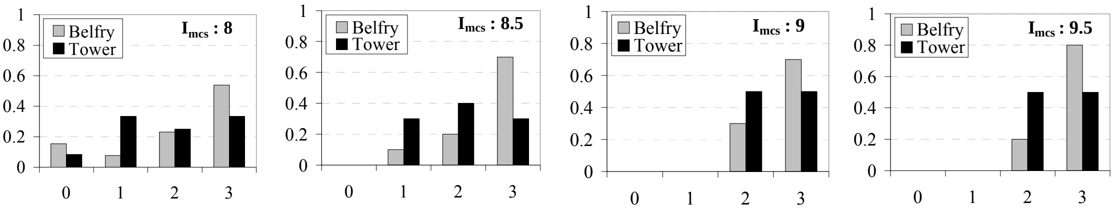

Figure 8 : Friuli damage probability matrices

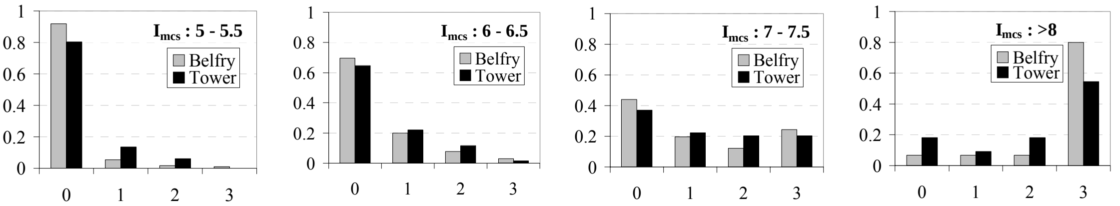

Figure 9 : Umbria damage probability matrices

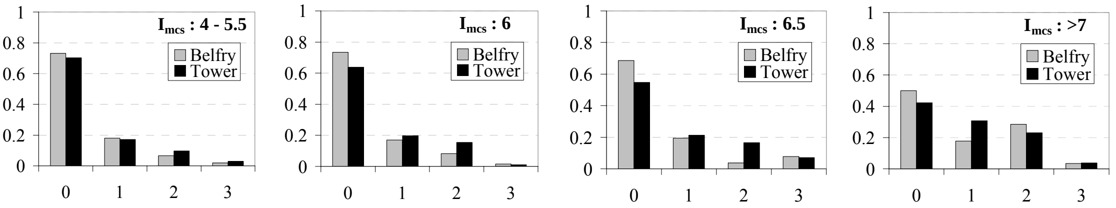

Figure 10 : The Marches damage probability matrices

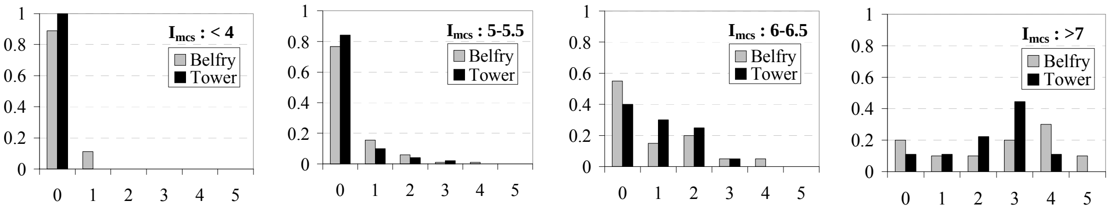

Figure 11 : Molise damage probability matrices

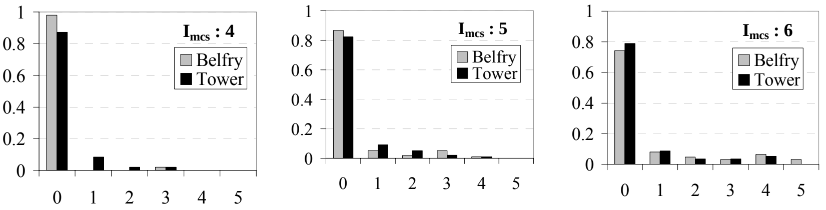

Figure 12 : Lombardy damage probability matrices

To discover whether the reason for this behaviour may only be understood as a function of the intrinsic vulnerability found, the data available was divided into two homogeneous classes in terms of vulnerability. This analysis was conducted for bell towers and belfries damaged by the earthquake in Umbria and the Marches in that they represent the most numerous and therefore most significant sample. For both macroelements, the subdivision into classes was carried out on the basis of the information contained in the survey form used in Umbria and the Marches which requires one to note any possible presence of two vulnerability indicators (Lagomarsino and Podestà 2004a). Elements for which at least one vulnerability indicator was present were considered as vulnerable, and elements for which both vulnerability indicators were absent were considered as non vulnerable.

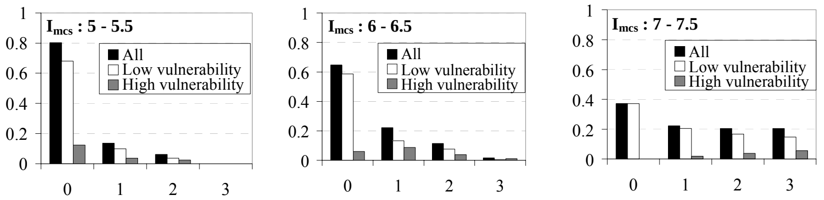

Figure 13 : Damage probability matrices in Umbria for tower macroelement

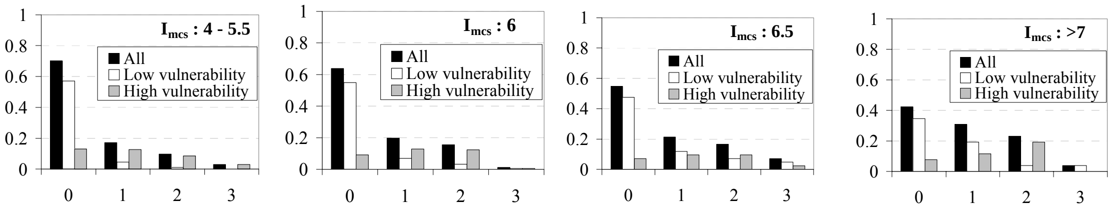

Figure 14 : Damage probability matrices in the Marches for tower macroelement

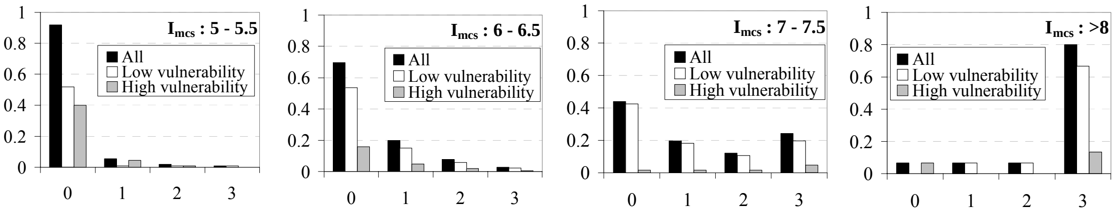

Figure 15 : Damage probability matrices in Umbria for belfry macroelement

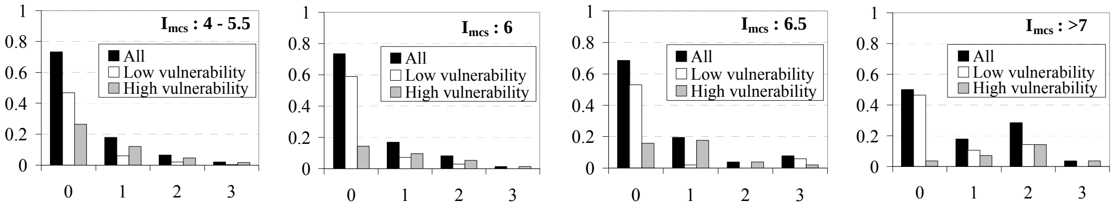

Figure 16 : Damage probability matrices in the Marches for belfry macroelement

Analysing the DPM it can be seen how for the tower macroelement the bipolar behaviour may be largely explained on the basis of the surveyed vulnerability (presence of vulnerability indicators). For what concerns belfries, instead, this analogous behaviour is not justified by the simple analysis of the influence generated by the vulnerability sources on the damage level. This aspect highlights how a vulnerability analysis conducted at a national level according to a macroseismic approach cannot be sufficient to completely undestand the seismic behaviour of belfries, pointing out the need to take into consideration the dynamic parameters at play (seismic input at the base, filter effect of the structure, dynamic features of the belfry, etc.).

4 CONCLUSIONS

The systematic damage assessment, after recent seismic events, has put in evidence that the belfry represents, mainly for severe earthquakes, the most vulnerable architectonical element. The reasons of this behaviour have to be found both in their intrinsic vulnerability (pier slenderness, masses at the top, static horizontal thrusts) and in the dynamic features of the seismic input. The acceleration time-history is different in comparison with the seismic input at the base of the tower, for the filter effect of the whole structure. The dynamic and the statistical analisys carried out, have confirmed the need to take into account of the dynamic parameters of the problem for a realistic seismic response prevision.

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