Seismic vulnerability of churches in Faial and Pico islands, Azores

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SUMMARY:
Earthquakes represent one of the main cause of serious damage and loss of historic and architectural heritage. Interventions to preserve these building should start with a careful knowledge and assessment of their seismic vulnerability, in order to support any needed retrofitting and strengthening measures.
This paper proposes a procedure to register and diagnose of the level of damage on churches after the occurrence of an earthquake, and also to assess the seismic vulnerability of this type of construction. This procedure was applied to sixteen churches in the Azores islands which were hit by the July 9th 1998 earthquake.
Belfries of church towers are elements with a particular seismic vulnerability. For this reason, and based on the Italian methodology proposed by the Linee Guida (2006), it is applied to belfries of two churches from Pico (Azores), a simplified mechanical model for assessment of seismic vulnerability of this type of structures.

Keywords: Seismic vulnerability, assessment methodology, churches

1. INTRODUCTION

Historic buildings were in general constructed using special constructive techniques and materials to reach large spans and extremely slender structural elements. These characteristics, which are particular to this type of construction, give these buildings a very high seismic vulnerability (Lagomarsino, 2006). Interventions to preserve these building should start with a careful assessment of their seismic vulnerability, in order to support any needed retrofitting and strengthening measures. According to Roque (2002), churches are well referenced and documented testimonies of the historical heritage, with the particularity of had suffered, and in some cases resisted, to violent earthquakes just like they were submitted to real scale seismic tests.

The seismology of the Azores archipelago (Portugal) results from the volcanic and tectonic activity of the Mid-Atlantic Ridge and is characterized by a large number of seismic events. On July 9th 1998 a 6.2 magnitude earthquake (Richter scale) was registered in Azores, with the epicentre located only 5 km north-east of Faial Island, which caused the collapse of more than 700 buildings and serious damage to public infrastructure and churches (Figure 1).

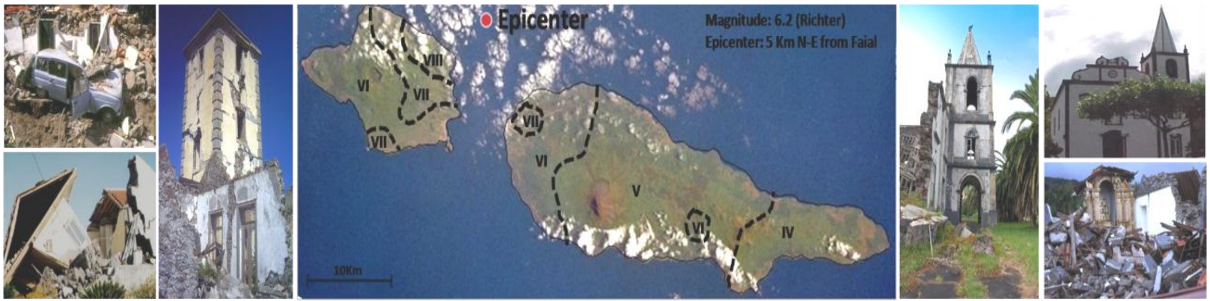


Figure 1. Epicentre location and isoseismals of the July 9th 1998 earthquake (adapted from Oliveira, 1998)

Seismic vulnerability assessment methodologies have been developed and improved by the necessity to preserve historic heritage. Making an accurate vulnerability assessment and classification of damage after the occurrence of an earthquake should contribute both to accurate retrofitting (with the intent of improving the seismic behaviour of the building) and significantly reduce the reconstruction costs of these buildings.

2. INSPECTION, REGISTER AND SEISMIC RISK ASSESSMENT

In the present work, the assessment of the seismic vulnerability and damage of the churches hit by the earthquake in 1998 is based on the methodology presented by the Italian group of earthquake defence GNDT (Gruppo Nazionale per la Difesa dai Terramoti). This methodology identifies 28 damage mechanisms related to the behaviour of the different macro-elements of churches (Figure 2) during an earthquake.

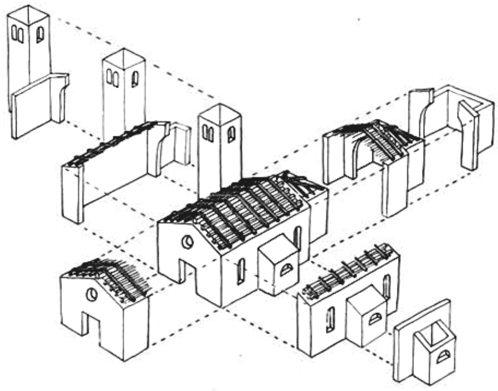


Figure 2. Main macro-elements that constitute the church [Doglioni *et al.*, 1994]

However, during evaluation of the photographic register and inspection reports made by Costa and Vasconcelos (1999), it was detected that all these churches contain a high choir and, most of them had damages related to the seismic behavior of this macro-element (Figure 3). This structure constitutes a second floor of the church, which normally includes access to the bell towers, and is a typical macro-element in Portuguese churches.

Figure 3. Consequential damages of the interaction between high choir and sidewalls of Azores churches [Costa and Vasconcelos, 1999]

The study of this macro-element is extremely important due the register of serious damages (Figure 3) that may result from its interaction with other parts of the structure, for example, the sidewalls, arches that support the structure or the façade. For this reason it was introduced as the 29th damage mechanism on the methodology corresponding to this macro-element. Figure 4 presents all the damage mechanisms considered in this work.

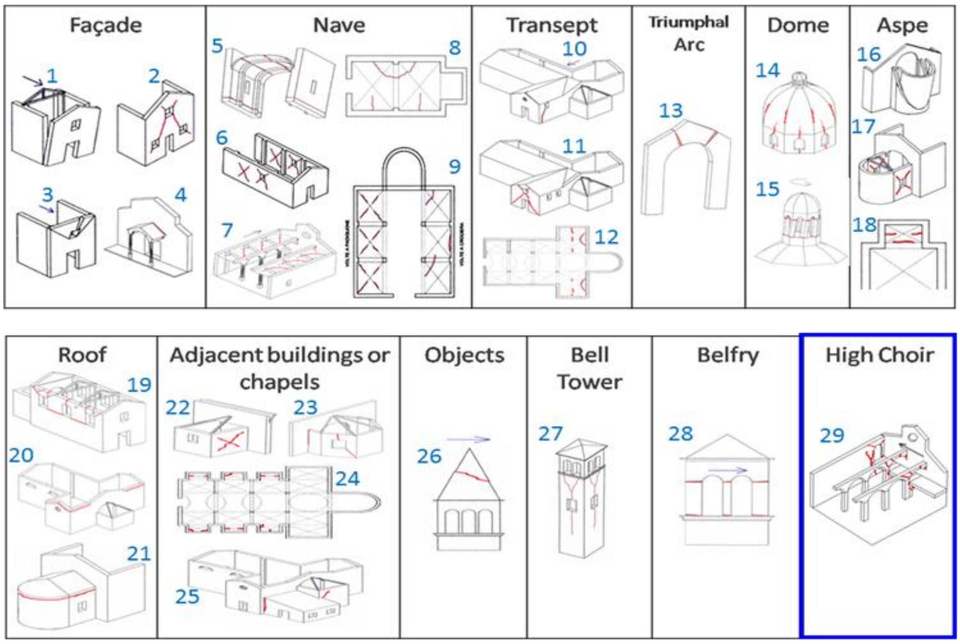


Figure 4. Damage mechanisms (adapted from *Linee Guida*, 2006).

2.1. Inspection sheet

To apply the methodology developed by the GNDT to the churches of Faial and Pico, a sheet was created to list the damage that occurred from the earthquake and to assess their seismic vulnerability, using as a base the approach presented in Ministero dei Beni Culturali and dei Lavori Pubblici (2003).

This sheet is divided in three distinct parts. The first part contains the general description of the structure, such as the identification of the church, its location, historic information about the construction and previous interventions, geometric characteristics, materials properties, and photographic register, among others important data needed for a detailed analysis of the structure. In the second part, a classification is made for the different damage mechanisms observed, as well as the vulnerability associated with each mechanism. The third part corresponds to the estimate of the damage index (i_d), vulnerability index (i_v) and seismic security index (I_s), according to the LV1 (*Livello di valutazione 1*) presented by the document *Linee Guida* (2006). These expressions were adapted due to the introduction of the new mechanism. This study was supplemented with the development of a database with the aim of organizing and storing all the information collected in the inspection sheets. These kinds of databases are very useful to support activities and decisions related to intervention priorities in a post-earthquake situation or for reinforcement to prevent future damages.

In the second part of the sheet, each damage is classified on a scale from 0 to 5 (parameter d_k), with "0" indicating an absence of damage and "5" corresponding to a collapse of the element in accordance with the European Macrosseismic Scale (Grünthal, 1998). The damage mode is already defined for most damage mechanisms by the C.N.R. (2002) and can be type I, corresponding to the behavior of the macro-elements out of their plan, or type II associated to the response of the walls on their plan (typically due shear and bending). The coefficient ρ_k represents the influence of the damage in the whole building. In some damage mechanisms, this value can be assumed to be between 0.5 and 1, depending of their relevance in the studied structure, with 1 representing elements of high importance and 0.5 to less important elements.

In relation to the seismic vulnerability assessment (vulnerability index i_v), in this part of the inspection form there are two parameters to classify: i) $v_{k,p}$which represents the technological and construction features that can attenuate the appearance of the mechanism; ii) $v_{k,i}$ the constructive characteristics or weaknesses that can led to the activation of the damage mechanism. These parameters are classified on a scale from 0-3, according to their effectiveness or relevance in the activation of the mechanism, as proposed in the manual developed by the C.N.R. (2002).

Similar to the guide from C.N.R. (2002) for the 28 damage mechanisms, it is necessary to define rules to classify the parameters $v_{k,i}$ and $v_{k,p}$ associated with the vulnerability of the high choir (mechanism 29), such as support conditions, type of structure, connections with adjacent macro-elements (sidewalls and façade), number and size of windows or doors on sidewalls, and other important construction approaches or techniques that can affect the behavior of this macro-element to seismic action.

Figure 6 represents the damage mechanisms identified in the sixteen studied churches. This figure indicates that the cracking caused by shear effort in the façade wall (mechanism 3), the overturning of the top of the façade (mechanism 2), damages in the high choir (mechanism 29) and the cracking in bell towers (mechanism 27), have been identified in a large number of the study cases. Analysis of this figure allows an indirect perception of the main weaknesses in these buildings.

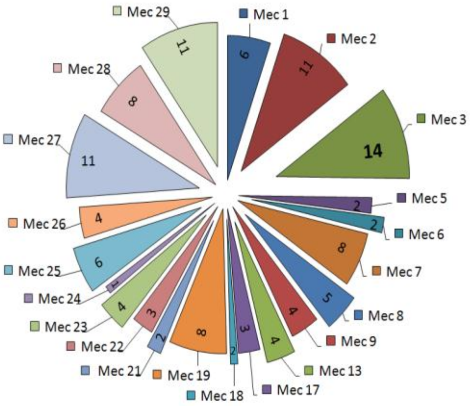


Figure 6. Pie chart of the identified damage to the 16 churches of Azores after the July, 9th 1998 earthquake

2.2. Determination of damage, vulnerability and seismic safety indexes

After the identification and classification of the damage level and seismic vulnerability associated with each macro-element, the third part of the inspection form was developed with the aim of automatically estimating the damage index (i_d), vulnerability index (i_v) and seismic security index (I_s), using the expressions presented by the *Linee Guida* (2006). These expressions were adapted in order to consider the introduction of the new mechanism:

$$i_d = \frac{1}{5} \times \frac{\sum_{k=i}^{29} \rho_k \times d_k}{\sum_{k=i}^{29} \rho_k} \tag{1}$$

where: ρ_k is the importance attributed to each mechanism; d_k corresponds to the damage level.

The value of damage index (i_d) can range between 0 and 1 and, according to the original document, it is considered that for 0.3 or superior values the church does not meet the minimum conditions of security for safe use.

$$i_v = \frac{1}{6} \times \frac{\sum_{k=i}^{29} \rho_k \times (v_{ki} - v_{kp})}{\sum_{k=i}^{29} \rho_k} + \frac{1}{2} \tag{2}$$

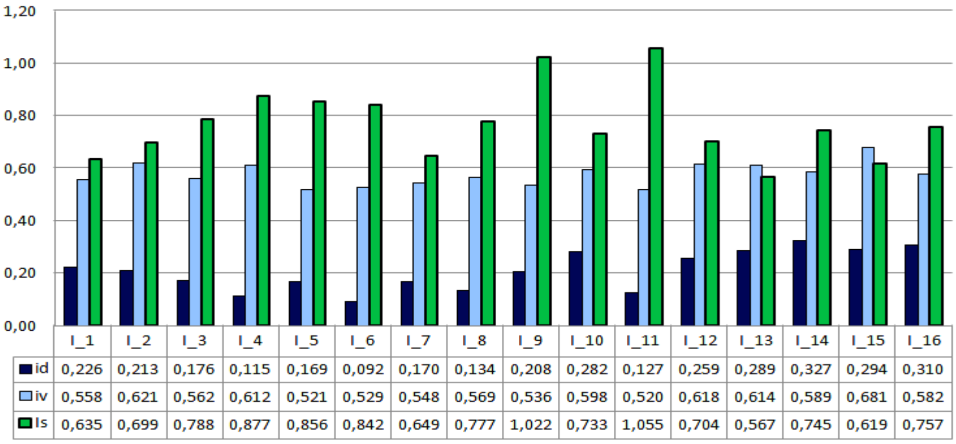
where: ρ_k is the importance attributed to each mechanism; $v_{k,i}$ corresponds to the construction limitations or weaknesses that can lead to the activation of the damage mechanism; and $v_{k,p}$, the technologic and constructive solutions that can minimize the activation of the mechanism.

$$I_s = \frac{a_{ELU}}{\gamma_1 \times S \times a_{gR}} \tag{3}$$

where: γ_1 represents the importance factor of the church; S and a_{gR} are respectively the parameter that corresponds to the ground amplification factor and the reference acceleration according to Eurocode 8 (CEN, 2004) for the seismic zone in analysis; a_{ELU} is the ground acceleration in relation to the ultimate limit state and it is given by the expression:

$$a_{ELU} = 0.025 \times 1.8^{5.1-3.44 \cdot i_v} \tag{4}$$

Figure 7 presents the values of these three indexes for the sixteen churches considered in this study.



	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_10	I_11	I_12	I_13	I_14	I_15	I_16
■ id	0,226	0,213	0,176	0,115	0,169	0,092	0,170	0,134	0,208	0,282	0,127	0,259	0,289	0,327	0,294	0,310
□ iv	0,558	0,621	0,562	0,612	0,521	0,529	0,548	0,569	0,536	0,598	0,520	0,618	0,614	0,589	0,681	0,582
🟩 Is	0,635	0,699	0,788	0,877	0,856	0,842	0,649	0,777	1,022	0,733	1,055	0,704	0,567	0,745	0,619	0,757

Figure 7. Values of i_d, i_v and I_s obtained for the 16 studied churches

As discussed previously, according to the reference document, churches with a damage index higher than 0.3, do not gather the necessary conditions for normal use. In this study, the value of this index was typically quite low, being equal to or greater than 0.3 in only in two of the sixteen churches.

The global seismic behavior of these buildings is statistically represented by the vulnerability index (i_v) (variable between 0 and 1), which is an average of the behavior of different parts of the church (*Linee Guida*, 2006). As shown in figure 7, all of the churches examined have a high vulnerability index (i_v) between 0.5 and 0.7

Regarding the seismic security index (*Is*), in most cases the values achieved were less than one (Figure7), which, according to *Linee Guida* (2006), means that these churches are not able to support an earthquake with the reference ground acceleration considered for this region ($a_{gR} = 2{,}5\ m/s^2$) (NA, 2008). It is important to stress that the results obtained for the seismic security index (I_s) concern the reference acceleration (a_{gR}) off the seismic region and depends also of the assumed values of ground amplification factor (*S=1*) and importance factor (γ_1=0.80).

3. SEISMIC VULNERABILITY OF BELFRIES – SIMPLIFIED MECHANICAL MODEL

According to Linee Guida (2006), the seismic behavior of macro-elements such as towers, bell towers and other high slender structures, depends on some specific factors such as: the slenderness of the structure, the damping degree of the walls, the eventual presence of smaller adjacent buildings or, for example, the presence of slender architectural elements in the top (pinnacles, belfry, etc.).

Bell towers are frequently in contact with the main structure of the church, which may induce horizontal limitations that deeply modify the behavior of the macro-element to seismic action. In all the studied cases, as with most churches in the Azores, we find that the bell towers are connected or incorporated into the main structure of the church. Although this reduces the effective slenderness of the element, it may also result in a local rigidity and concentration of loads, and therefore be the cause of significant damage. In the bell towers, the belfry can be a particularly vulnerable element, due to the existence of large openings, normally constituted by slender columns with reduced axial loads

3.1. Method description

The damage mechanisms associated with this type of structures depends on their construction and geometric characteristics. For a quantitative assessment with simplified mechanical models, it is possible study the collapse by bending with axial force and considering the towers as a cantilever, submitted to a system of horizontal forces combined with their weight that can cause, in a generic section, the crushing in compression zone, after cracking caused by the lack of tensile resistance of the masonry.

The assessment of these slender masonry structures to bending with axial force is made by comparing the design value of applied bending moment correspondent to the reference acceleration ($\mathrm{M_u}$), and the resistant bending moment calculated to ultimate limit state ($\mathrm{M_{res}}$). This approach assumes that the masonry doesn't have tensile resistance and it is necessary to consider a nonlinear distribution of the compression (Linee Guida, 2006).

The reference document also allows the calculus of the ground acceleration corresponding to the ultimate limit state ($\mathrm{a_{ULS,i}}$) that should be compared to the reference ground acceleration ($\mathrm{a_{gR}}$) to allow a complete safety verification of the structures.

3.2. Application of the simplified mechanical model to belfries of two churches

The simplified methodology presented in this study was applied to the towers of two churches in Pico Island hit by the 1998 earthquake. In the church of Bandeiras the towers are connected to the church, while the church of Madalena has incorporated towers. However the application of this simplified mechanical model is equivalent in these two cases, because it should be analyzed only the free part of the towers that correspond, in both cases, to the belfry zone (Figure 8).

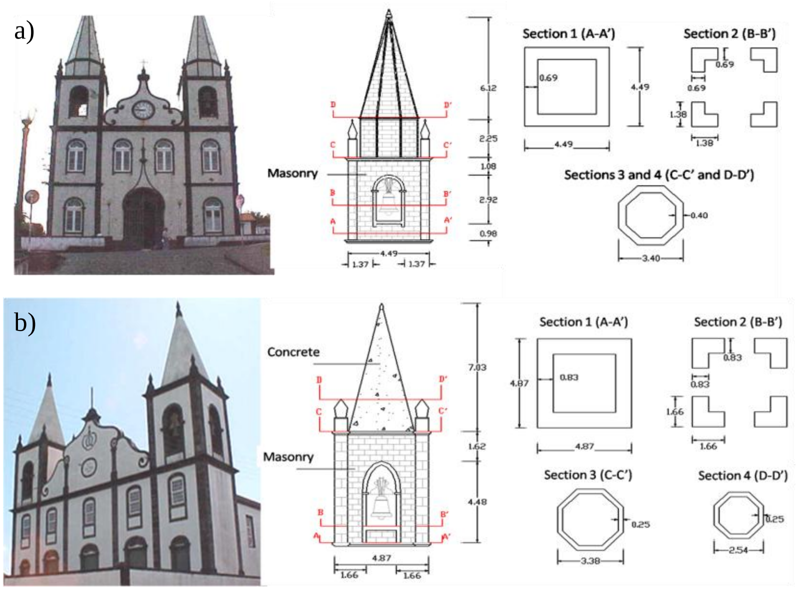


Figure 8. a) Church and belfry of Madalena – Pico; b) Church and belfry of Bandeiras – Pico

In both cases it was verified that the critical section corresponds to the base of the columns on the belfry, easily explainable by the reduced dimensions in plant of the elements besides of the reduced axial load at this level. Comparing the resistant bending moment ($\mathrm{M_{res}}$) with the bending moment corresponding to the reference acceleration ($\mathrm{M_u}$) of the critical section (Table 1), it was concluded that this condition was verified. In addition, the results obtained by the critical ground acceleration corresponding to the ultimate limit state (a_{ELU}) are lower than the reference ground acceleration (a_{gR}) for this region ($a_{gR} = 2{,}5\mathrm{m/s^2}$) indicating their high vulnerability.

Table 1. Values obtained for the critical section of belfries of Madalena and Bandeiras churches

Belfry	Height (m)	Altitude of critical section (m)	Dimensions of columns (m)	Vibration period, T (s)	M_{res} ($kN \cdot m$)	M_u ($kN \cdot m$)	a_{ELU} (m/s^2)
Madalena	7.12	0.95	0.38 x 0.38	0.2179	552.74	41.67	0.886
Bandeiras	7.83	1.01	0.66 x 0.66	0.2345	894.92	57.59	1.201

It is important to stress that the real height of the belfry was not considered in this analysis. For this reason, it was calculated the values of the critical ground acceleration in the case of the belfries on the top of an isolated tower (Figure 9), assuming that the bell towers are not in contact with the remaining portion of the church structure. The results obtained for the two situations for the both studied belfries are presented in Table 2.

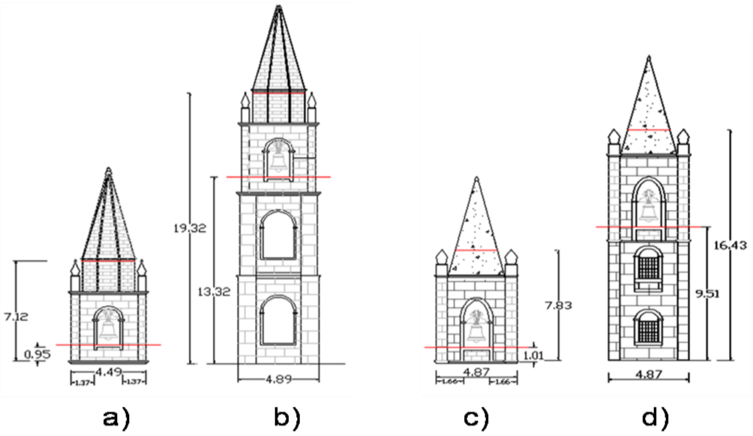


Figure 9. Critical sections in the two considered situations: a) Church of Madalena only considering the belfry; b) Church of Madalena considering the isolated tower; c) Church of Bandeiras only considering the belfry; d) Church of Bandeiras considering the isolated tower.

Table 2. Values obtained for the critical section considering only the belfry or the entire tower

	Belfry of Madalena (a)	Bell Tower of Madalena (b)	Belfry of Bandeiras (c)	Bell Tower of Bandeiras (d)
Total height (m)	7.12	19.32	7.83	16.43
Altitude of critical section (m)	0.95	13.32	1.01	9.51
Weight (kN)	973	4143	1239	3258
T (s)	0.2179	0.4620	0.2345	0.4086
M_{res} ($kN \cdot m$)	552.74	411.46	894.92	650.97
M_u ($kN \cdot m$)	41.67	260.46	57.59	240.16
a_{ELU} (m/s^2)	0.886	0.844	1.201	0.895

The results obtained for the critical ground acceleration showed that both the belfries have high vulnerability to seismic action, and the ground acceleration corresponding to the collapse in the critical section diminishes when the real altitude of the belfry is considered. This increase in vulnerability is caused by the amplification of ground acceleration at the real altitude of the belfry.

The biggest increase of vulnerability corresponds to the church of Bandeiras (lower tower). These results are justified by the number and dimensions of considered openings providing to this tower a higher seismic vulnerability, and to the fact of its lower fundamental vibration period, being in this case the response spectrum more severe.

4. CONCLUSIONS

The main aim of this work was asses the seismic vulnerability of the religious heritage of Faial and Pico islands. This was developed with the intent of improving present inspection and registration methods for evaluating the seismic safety or vulnerability of this type of historical building.

The development of inspection strategies and inventorying damage to churches constitutes a very useful tool for the assessment of these buildings after the occurrence of an earthquake. It is also possible to use this information to determine intervention priorities. Moreover it allows the identification of weaknesses associated with each macro-element, supporting intervention strategies to improve the structures behavior to seismic action.

The application of the mechanical model presented by the *Linee Guida* [2006], despite being a simplified method of vulnerability assessment, allows us to identify with exactitude the critical section of elements such as belfries and isolated bell towers. This methodology also allows the calculation of the ground acceleration value corresponding to the collapse ($a_{ULS,i}$) of this section for bending with axial force.

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