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THE ST. SILVESTRO BELFRY IN L'AQUILA: FROM THE REHABILITATION WORKS TO THE ACTUAL PERFORMANCE IN TERMS OF DYNAMIC PROPERTIES AND FRAGILITY FUNCTIONS ESTIMATION

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Abstract. *Masonry towers are widespread ancient constructions, located even in seismic zone. The assessment of their seismic capacity is a required task owing to the vulnerability and predisposition to suffer damage. Slender structures are also involved in peculiar dynamic behavior, like torsional mode shapes and acceleration amplification at height. The accuracy of the seismic response prediction depends by the knowledge of geometry, masonry properties and constraint boundary conditions, frequently uncertain. The authors investigated the seismic behavior of a tower, the St.Silvestro belfry in L'Aquila (Italy). The St.Silvestro complex was hit by the 2009 earthquake. The rehabilitation works was finalized to mitigate the vulnerabilities of the masonry complex. The results of operational modal lead to the updating of a finite element model, in terms of dynamic properties. The seismic performance of the belfry are assessed in terms of probability of collapse and revealed through fragility curves.*

1 INTRODUCTION

Masonry towers (MTs) are cultural buildings disseminated in urban contest, even in areas with high seismic hazard, isolated or included in the clustered buildings. In ancient times, MTs were conceived to withstand only gravity loads. Their vulnerability under horizontal loads is ascribed to the brittleness of the masonry and the geometric configuration. The poor quality of the masonry combined with the specific vertical configuration yields considerable tensional state at the basement, seismic amplification at height and dynamic phenomena which are uncommon for ordinary masonry constructions. Furthermore the geometric irregularities could worse the damage patterns and surrounding buildings could modify the seismic response, reducing the slenderness. Nevertheless, the induced damages by seismic events provide information about their dynamic behavior. Generally, the most frequent response of the steam of MTs is exhibited in local mechanisms, like overturning. While the upper part of the tower is involved in the rotation and sliding of the pillars, causing cracks in the arches, due to the lack of tie rods or hooping ties, slender pillars and roof too heavy and/or thrusting. Nevertheless, several structural configurations could modify the failure modes, worsening a damage pattern or causing specific cracks. The analysis could include the whole of the structural parameters to foresee a realistic response, on which the protection measures could evaluated. A strategy to reduce the uncertainties of the unknown parameters is a deep investigation, through a complete diagnostic and a critical analysis. Unfortunately, the knowledge is not feasible owing to the lack of historical data and the impossibility of invasive and destructive test. But a meaningful strategy to foresee a realistic structural response is the development a synergic integration between numerical and experimental analysis. To this aim, Operational Modal Analysis (OMA) is a powerful method that allows the investigation of modal parameters in a non-invasive way. The authors performed several studies on the seismic behavior of a masonry tower, the St.Silvestro belfry. The operational modal analysis and the numerical modeling are performed. In this paper the actual dynamic response of the belfry is investigated through the OMA. After that, the seismic performance, in terms and the derivation of fragility curves, are evaluated on a refined finite element model of the structure.

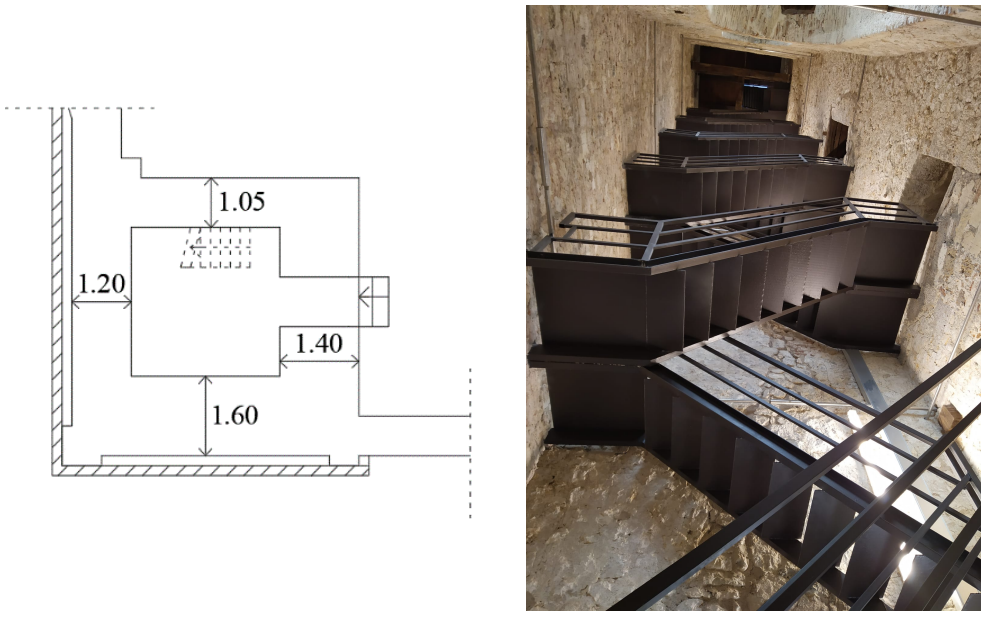
2 THE INVESTIGATED CASE STUDY: ST.SILVESTRO BELFRY IN L'AQUILA

2.1 Description of the building

St.Silvestro complex is a monumental building, situated in L'Aquila (Italy), built between XIII and XIV century, during the dominance of the king Federico II. The interior is divided in three naves of which the length of the central is twice of the lateral ones. Ogival arches separate the naves and support a masonry wall with a thickness of 80 cm and a height of 5 meters. The symmetric facade has a large Gothic window. While, the belfry is located in the right side of the church façade and it is as long as the lateral nave. It presents a rectangular plan with 5.5 and 6.9 meters per sides. The height of the tower is 33 m. A steel staircase arrives at the bell cell, characterized by slender masonry piers and large windows. The thickness of the masonry changes in correspondence with each wall: 1.05, 1.20, 1.40 and 1.60 m. The complex was built in local masonry [1], with irregular units arranged in irregular texture, namely "Apparecchio Aquilano".



Figure 1: Panoramic view of St.Silvestro church.

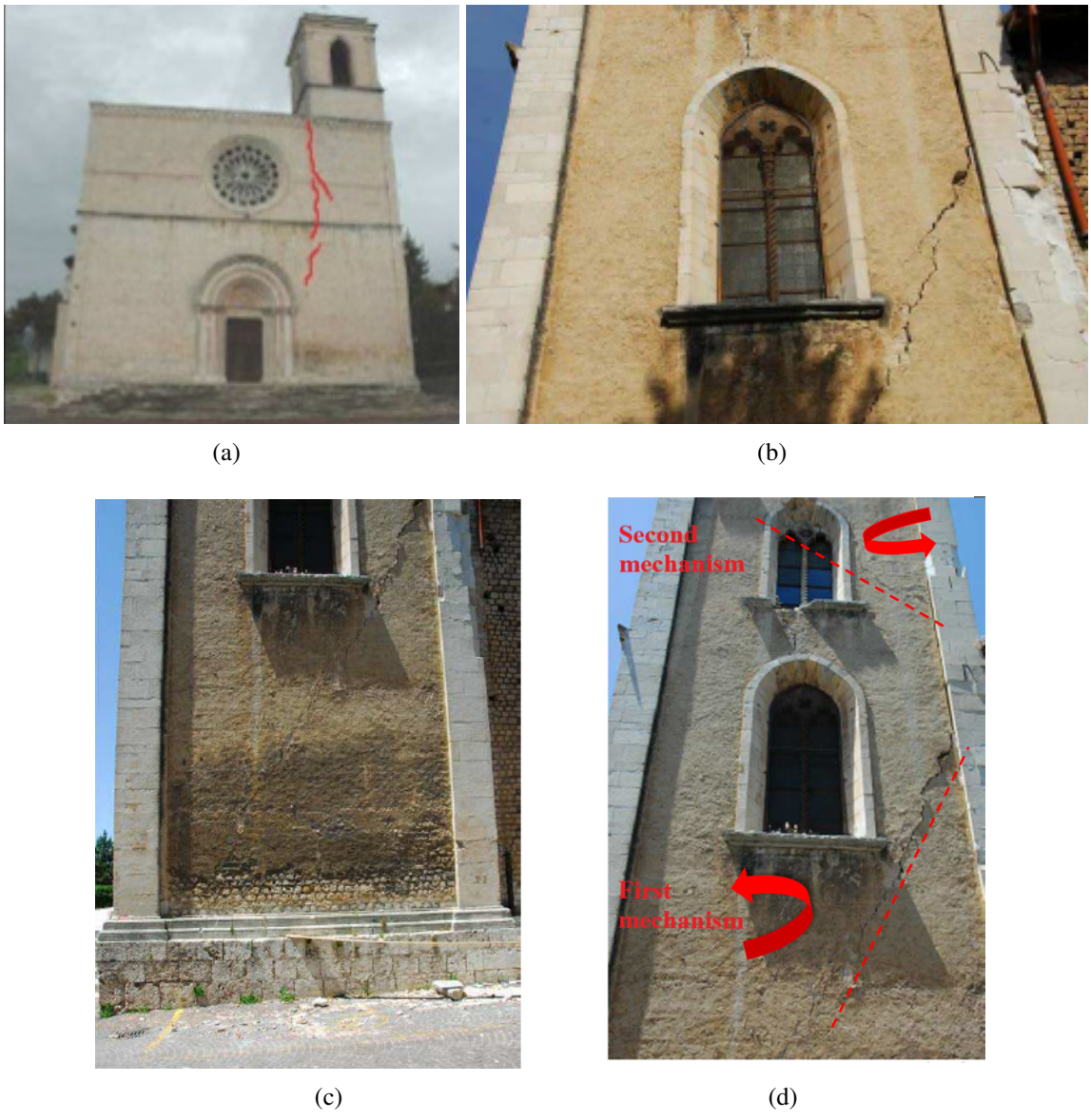


(a) (b)

Figure 2: Cross-section of the masonry tower (a) and the detail of the steel staircase inside the bell tower (b).

2.2 Suffered damage and underwent restorations

During the earthquakes swarm in 2009, the bell tower exhibited a local response. In particular, the visible damage pattern identified two overturning mechanism, like marked in red in Fig.3. The first mechanism involved the entire MT in a composed overturning around a cylindrical hinge located at the basement.



(a) (b)

(c) (d)

Figure 3: Crack scenario and schematisation of collapse mechanisms of the bell tower after the earthquakes (from the Fine Art Authority on-line site).

The second mechanism involved the upper part of the belfry in an overturning around a cylindrical hinge located at the gutter of the church (at 10.20 meters from the basement). These kinds of seismic response are a peculiar dynamic behavior of historical buildings. In fact, the lack of connection wall-to-wall and floor-to-wall is the main structural feature that induces a local response, as out of plane mechanism of the walls. Monumental buildings are often characterized by poor quality of masonry due to decay and arrangement over time, leading to a local collapse, even earlier to exhibit a out of plane response.

Based on the surveyed damage, the restoration of the St.Silvestro belfry focused on the repair of damage, closing the cracks by horizontal stone connections and injections. Whereas the reinforcement was finalized to assign a box-like behavior. Inserted steel rods avoided the out of plane response, recovering the lack of connection. From a visual inspection, it is noted that the position of the steel rods is close to an old installation in wood realized in a past restoration. In fact, due to high seismic risk of L'Aquila, the use of the wood pervaded noble and poor buildings as anti-seismic timber devices [2].
Moreover, the reinforcement ensured the enhancement of the mechanical properties of the masonry thanks grout injections, respecting the architectural criteria.

3 APPRAISAL OF THE ACTUAL PERFORMANCE OF THE BELFRY

3.1 In situ dynamic investigation

The appraisal of the performance of monumental buildings, including masonry towers, requires a deep knowledge of the structural system, in order to achieve a high level of accuracy. The recourse to specific test ensures the characterization of the building. Non destructive test, like visual and non invasive inspections, are not always able to grasp the unknown parameters. For example, the reliability of the thermal camera is related to the thermal equilibrium of the wall. Whereas destructive test could be compromise the architectural value of the component of the building. Others methods rely on the identification of the dynamic properties of the structure in its in-situ condition whether the architectural value of monumental buildings or the utilization of the infrastructure requires non destructive test methods. A powerful on site dynamic investigation is the Operational Modal Analysis (OMA) technique. Among the algorithms in time domain, the Stochastic Subspace Identification (SSI) method is used for the estimate of modal parameters from Output Only measurements. The SSI method is classified as Covariance-Driven Stochastic Identification (Cov-SSI) and Data-Driven Stochatsic Subspace Identification (DD-SSI), that was generalized to a reference-based version (SSI-cov/ref) by Peeters and De Roeck [3].
The dynamic campaign on St.Silvestro belfry was performed on December 2019, in order to investigate the structure response under ambient vibration measurements. The setup of the campaign involved 10 biaxial accelerometers, of which 2 accelerometers provided a reference location [4], while the other 7 were placed in the inferior levels in several measurement points, as displayed in the layout depicted in Fig.4. The data were sampled at a rate of 250 Hz. The cut-off frequency of the anti-aliasing filter was set to 20 Hz. The number of samples was set to N=720000, which resulted in a measurement time of 1 hour. Data from multi-setup measurements, with 4 setups, were then merged following the approach recalled in [5]. Two modes arise from the stabilization diagram and revealed translation shapes, as reported in Fig.5.

3.2 Numerical modelling

The dynamic response of the St.Silvestro belfry is evaluated also through a numerical analysis. Two different structural models were adopted. A model, with bi-dimensional finite elements, was developed aimed to reproduce the refinement behavior of the belfry, used for the model updating. An equivalent frame model, with a one-dimensional finite element, was performed to overtake the computational burden of non-linear analysis. The finite elements consisted of four frames, with an equivalent section with each wall, resorting to lumped plasticity [6]. A rigid-perfectly plastic behavior with final brittle failure was assigned to all plastic hinges. The whole structure has been assumed fixed to the foundation, considering the soil-structure as

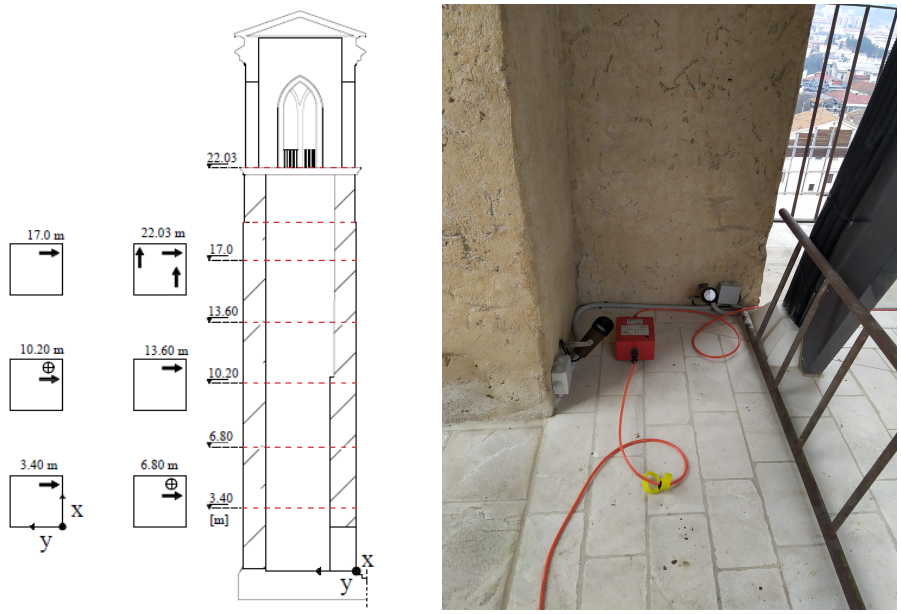


Figure 4: Experimental setup, showing the position of the accelerometers along the height of the tower. On the right: a sensor placed on the the top of the bell tower, at the height of 22,03 m.

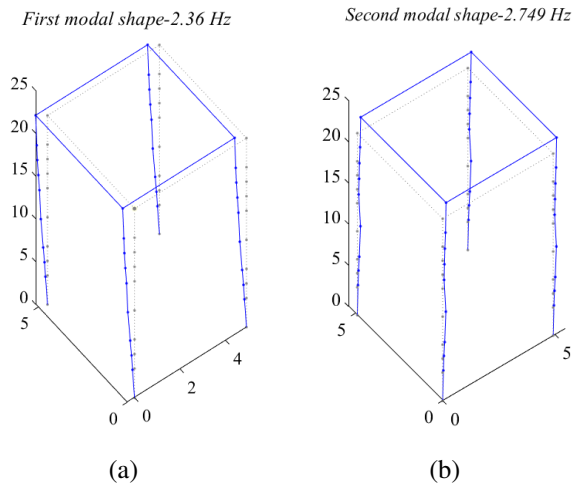


Figure 5: First two experimental mode shapes deriving from OMA.

negligible. The neighboring church was included in the model by non-linear springs. The mechanical parameters of the reinforced masonry are assigned starting from the value reported in the Italian Standard Code[7] for unreinforced masonry, as reported in Table 1, and applying the corrective factor for the restoration measure carried out.

Table 1: Mechanical parameters of irregular stone masonry.

Unreinforced masonry	f_m [MPa]	τ_0 [MPa]	E [MPa]	G [MPa]	γ [Mpa]
Irregular stone masonry	2	0.043	1230	410	21

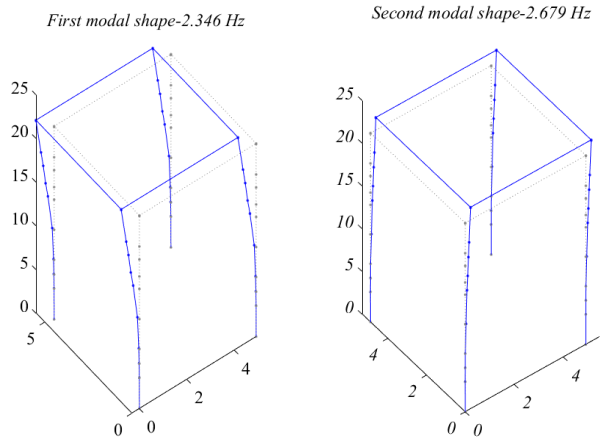
Starting from numerical results, the model updating was carried out.

3.3 Model updating of modal properties

The model updating aims to correct the finite element model by processing the results from dynamic test on the structure. To measure the distance between the estimated modal parameters and the numerical ones, the following objective function is used [8]:

$$C = \sum_{i=1}^{M} \gamma_i \left(\frac{\omega_i^m - \omega_i^c}{\omega_i^m} \right)^2 + \beta \sum_{i=1}^{M} (1 - diag(MAC(\Phi_i^m, \Phi_i^c))) \tag{1}$$

where the apex $(*)^m$ indicates a measured variable, the apex $(*)^c$ a calculated variable, Φ_i is the mode shape vector, M is the number of modes, MAC is the modal assurance criterion [9], while γ_i and β are weighting factors. The weighting factors are set equal to one.



(a) (b)

Figure 6: (a) First mode shape from model updating; (b) Second mode shape from model updating

The model updating was performed with the aim to detect the elastic modulus E of the masonry. According to the Italian Guidelines, an acceptable range for the modulus E value was investigated. The optimization led to a value of E for the walls in x direction equal to 3540 MPa, while the modulus for the y direction was identified to be equal to 3360 MPa [10]. The evaluated MAC takes the value equal to 0.78 for the first mode and to 0.88 for the second one, ensuring a consistent correspondence. The other values are negligible.

3.4 Derivation of fragility functions

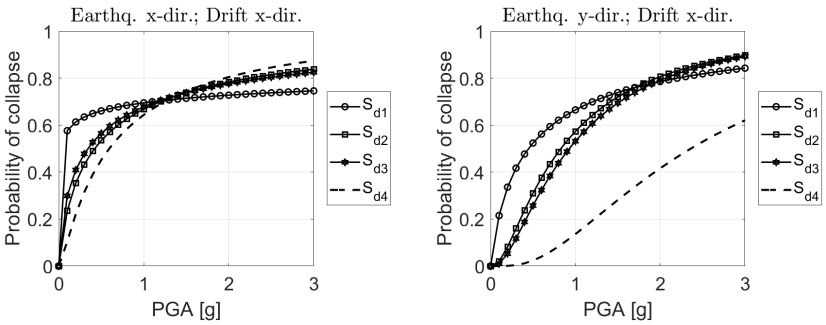
The seismic performance of the belfry, after the restoration, are estimated through fragility function. The probability of collapse of the structure is evaluated, for four limit states of interest, as a function of ground motion intensity measure, IM [11], which, in this paper, is the PGA itself. The occurrence or non occurrence of collapse is defined by the exceeding of a given displacement, for a given set of ground motion and dynamic structural analysis results. A lognormal cumulative distribution function is used for fitting the fragility function based on data collected from non linear dynamic analysis [11]:

$$P(C|IM = x) = \Phi\left(\frac{ln(x/\theta)}{\beta}\right) \tag{2}$$

where $P(C|IM = x)$ is the probability that a ground motion with $IM = x$ will cause the structure to collapse; Φ is the standard normal cumulative distribution function (CDF); θ is the median of the fragility function (the IM level with 50% probability of collapse); and β is the standard deviation of ln IM (sometimes referred to as the dispersion of IM). Since the truncated incremental analysis was carried out, an alternative procedure [11] to estimate the parameters θ and β is followed, obtained by varying the parameters until a certain likelihood function is maximized. Specifically, the parameters are obtained by maximizing the logarithm of the following likelihood function:

$$\{\hat{\theta}, \hat{\beta}\} = argmax_{\hat{\theta},\hat{\beta}} \sum_{j=1}^{m} \left[ln\Phi\left(\frac{ln(IM_i/\theta)}{\beta}\right)\right] + [n-m]\, ln\left[1 - \Phi\left(\frac{ln(IM_{max}/\theta)}{\beta}\right)\right] \tag{3}$$

where $\hat{}$ denotes an estimated parameter, $\Phi()$ the standard normal distribution PDF, n the number of ground motion used in the analysis, m the number of m ground motions that caused collapse at IM levels lower than IM_{max}, $\Phi()$ the standard normal distribution CDF. The parameters of Eq.(3) are estimated for each of the earthquake recordings. The resulting two parameters of the fragility function, representative of all considered seismic scenarios, are obtained taking the mean of all the couples of parameters estimated from each truncated incremental dynamic analysis. Fig.7 shows the obtained fragility functions, for the x direction, that reveals the high-



(a) (b)

Figure 7: Fragility curves of the numerical model of the masonry tower.

est value of probability of collapse due to the significant drifts in its direction of application. The in-homogeneous structural characteristics, in terms of the mechanical parameters and horizontal restrains, gives rise to the different probabilities of collapse. In detail, the restoration

works foresaw a different improvement of the mechanical property of the masonry, assigning different value of the elastic modulus and the strength resistance of the masonry. In addition, the horizontal constraint provided by the church is not the same between the two direction due to the different stiffness and connection of the adjacent masonries. Nevertheless, a further deep characterization is required in order to grasp the boundary conditions accurately.

4 FINAL REMARKS

A procedure for a reliable assessment of seismic response of a masonry tower is performed. The case study investigated is St.Silvestro belfry, located in the centre of L'Aquila and damaged by 2009 earthquake. By discussing the restoration works, the numerical and operational modal results, the paper aims at offering a reliable approach to obtain the seismic response with its confidence intervals. The prediction of the seismic performance of masonry towers is an tricky task, owing to the lack of the building knowledge. In order to overcome the uncertainties, an integrated approach between numerical and experimental analysis is a powerful procedure, as discussed in this paper. The experimental campaign has investigated the modal parameters of the St.Silvestro belfry. In particular OMA has allowed the evaluation of frequencies and modal shapes, taking into account the influences of neighboring construction, else uncertain. The model updating has founded the correspondence between the experimental data and numerical results. After that, the correct actual modal behavior is assessed. Furthermore the numerical model has yielded the seismic behavior in terms of fragility functions. Hence the integrated approach is capable to predict the seismic performance and the damage during the service condition or future earthquakes accurately, on which monitoring and retrofitting could be designed.

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The geometric survey and additional information of the monumental complex of St.Silvestro were found on the online site of Fine Art Authority.

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