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Earthquake protection of the *Torre Grossa* medieval tower of *San Gimignano*, Italy by vertical external prestressing

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ABSTRACT

This paper presents an application of a methodology for the seismic vulnerability reduction of masonry towers by reversible prestressing. The approach is applied on a medieval tower located in *San Gimignano*, Italy, which is considered as a world heritage site. The 3D FE models are calibrated with experimental data and assessed by nonlinear static analyses including the seismic demand of the site and an accurate validated masonry model. The vertical prestressing is applied at key points identified in the seismic vulnerability assessment. This technique is in compliance with the demand for architectural conservation because it may be fully reversible. The seismic performance is enhanced by increasing force, displacement and internal confinement. It is observed at ultimate limit conditions an upgrading of 14.3% of displacement with the medium prestressing level and 9.5% with the high level. The results are analyzed and discussed in terms of earthquake energy dissipation and failure mechanisms.

1. Seismicity of *San Gimignano*, Italy

The Tuscany region is surrounded and crossed by major mountain chains and is located in the north-central part of Italy, between the Tyrrhenian Sea and the central Apennines with an extension of about 22,990 km^2 (Fig. 1a). The Tuscany adjoins in the northern part with the regions of Liguria (NW) and Emilia-Romagna (NE), with Marche in the East and in the southern part with Lazio (SW) and Umbria (SE). According to the European Code (EC-8) [16], Italy is divided into four main seismic zones ranging from 1 to 4, where 4 represents a slight hazard; 3 moderate; 2 strong and 1 major (Fig. 1b). Taking into account this zonation, the earthquake (EQ) hazard of Tuscany may be classified into two main zones; moderate and strong seismic hazard, being part of the former the medieval town of *San Gimignano* (see Fig. 1).

Another important seismic hazard map of Italy was developed by the *Istituto Nazionale di Geofisica e Vulcanologia* [27], assigning to the region of *San Gimignano* an expected PGA between 0.125 and 0.150 g. The Italian peninsula is characterized by intraplate seismic activity, where the typical fault solution is represented by collision and strike-slip EQs [24]. Historically, the seismic activity of Tuscany is unusual and scarce. The June 29th, 1919 Mugello EQ (Mw = 6.3) was the strongest event ever documented [46]. This seismic event with epicenter at 25 km north of Florence caused in Mugello the death of >100 persons. Neither

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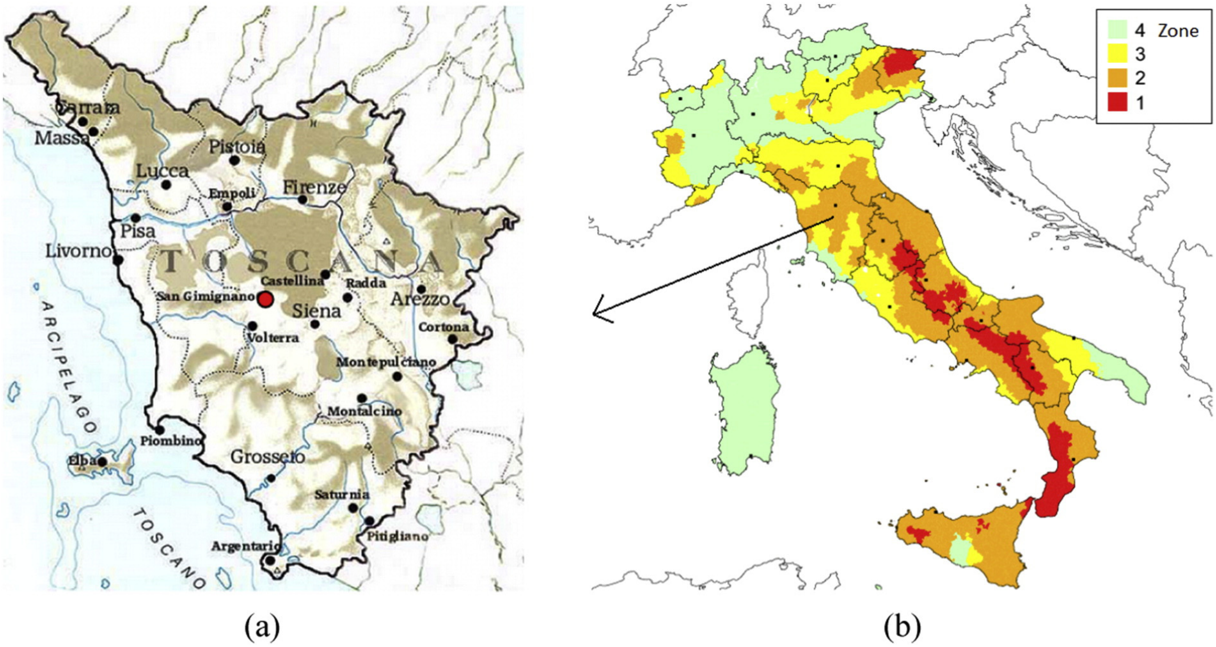

Fig. 1. *San Gimignano* seismic hazard; (a) Tuscany region and (b) seismic hazard regionalization of Italy, OPCM 3274–2003 [27].

casualties nor important structural damages were observed in neighboring towns. *San Gimignano* is geologically characterized by the presence of two different types of sedimentary deposits that were formed during the Pliocene era [44]. These deposits consist on Limestone rock and fine materials as sands and clays. The presence of limestone rock is due to the fact that the medieval town was built on the top of a hill with apparent stable soil conditions. Nowadays, there is not available information about the expected local site effects. According to the Italian code OPCM-3519-2006 developed by INGV [27], *San Gimignano* is characterized as a soil B and seismic hazard zone 2, with a maximum PGA (rock site) of 0.150 g and a probability of exceedance of 10% in 50 years (for a return period of 475 years). Taking into account the seismic hazard characterization, the parameters of Table 1 and a soil factor of 1.2, it is expected a maximum acceleration at the site of 0.18 g. With this data, it is possible to construct the elastic response spectrum, which will be used to represent the seismic demand of the site through the nonlinear analyses (Fig. 2b).

2. History and actual damage state of the *Torre Grossa*

San Gimignano is a medieval town located in the province of Siena, in the Tuscany region and is internationally known by its tall ancient masonry towers and surrounding bare-stone walls. The town has its origins in the III Century and was a reference point for Catholic pilgrims in their journey to the Vatican in Rome. Wealthy families of *San Gimignano* built >72 masonry towers and nowadays only 17 exist including the *Torre Grossa*. This tower is the tallest among the existing ones and is located at the main square as illustrated in Fig. 2a. Bartoli et al. [4,5]) describe that this tower was approximately built in the first part of the XIII century (approximately in 1240) and is the tallest and most important among the preserved towers in the medieval town. Its cross section is square, with dimensions of 9.5 × 9.5 m and a total height of about 60 m with walls of variable thickness (2.6 to1.6 m). The walls are made of three-layer masonry (also named *sacco* in Italian). The external layer is constituted by carved lime stone and mortar, the internal by brick masonry and the filling by remains of bricks in a matrix of poor mortar. At the height of 20 m, the tower is incorporated to the neighbor Town Hall (*Palazzo Comunale*) which was previously constructed. The floors were built with vaults of brick masonry and an internal steel-stair permits to reach the top of the tower. The slab was recently reconstructed by the use of reinforced concrete. Nowadays, the former heavy bells were removed and it was installed at the top of the tower a conjunct of bells of reduced size and a ringing of bells system made of a steel frame. This engineered system was made with the purpose of transmitting to other resistant elements the lateral and vertical forces induced by the ringing of bells, which may cause vertical cracking due to the concentration of tensile stresses.

In 1632, the *Torre Grossa* was severely damaged due to a lightning, causing the partial collapse of a wide part of the SW façade. About 17 years later, the collapsed part was re-constructed. Nowadays, the tower presents important vertical cracks (see Figs. 2a

Table 1
Parameters describing the elastic response spectrum for *San Gimignano*.

Seismic hazard	Ground type	S	T_B (s)	T_C (s)	T_D (s)
Zone 2	B	1.2	0.15	0.5	2.0