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Case study

Earthquakes and ancient leaning towers: Geodetic monitoring of the bell tower of San Benedetto Church in Ferrara (Italy)

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ABSTRACT

In May–June 2012, several seismic events took place in the Po River Plane in northern Italy, with a maximum magnitude of M_W 5.86 (M_L 5.9)] and the epicentre located about 32 km from the centre of Ferrara. Many historical buildings were seriously damaged and others showed marked deformations or differential settlements. Therefore, it was necessary to place many of them under monitoring, using fast and safe measurement techniques to quickly obtain accurate information on ongoing structural deformation. This paper presents the case study of the bell tower of San Benedetto Church in Ferrara (17th century), which was already under monitoring at the time of the earthquake because of its remarkable leaning angle. Immediately after the seismic events, monitoring of the bell tower was repeated. Digital levelling indicated a marked differential settlement of the foundations with regard to the trend of secular movement, while terrestrial laser scanning (TLS) revealed a significant increase of the inclination of the tower's axis, confirming the results from levelling and showing good integration of both monitoring techniques.

1. Introduction and research aims

Monitoring and safety evaluation of leaning towers represent a primary task in cultural heritage management. Italy is particularly rich in these "long constructions" and quite often towers are synonymous with leaning towers due to poor mechanical properties of the soil. In some famous case studies such as the "Torre di Pisa" [1], the "Torre degli Asinelli" in Bologna and the "Ghirlandina" in Modena [2], monitoring revealed that the towers are affected by progressive differential settlement of the foundation, causing an increased inclination of the axis. In the case of the "Torre degli Asinelli", a change in the shape of the masonry structure was also shown by repetition of TLS surveys in time [3]. The consequence of these phenomena is increased risk of a collapse of the structure as well as heightened seismic vulnerability of the whole construction [4].

This means that a complete geodetic monitoring of a tower structure affected by both rigid movements and shape variation must consist in at least digital levelling at the base for high-precision control of the differential subsidence of the foundation and TLS to determine the shape variation of the whole structural complex. Laser scanning also provides the data necessary to use 3D models to evaluate the seismic vulnerability of the structure.

The bell tower of San Benedetto Church in Ferrara (Italy) is an interesting case study. In 2003, a program was started to monitor settlements of the foundation, first by digital levelling and later by TLS. Levelling indicated a significant rotation of the base of the tower, while TLS confirmed the consequent increase of the out of plumb.

In May–June 2012, Ferrara was affected by several earthquakes with a maximum magnitude of M_W 5.86 and the epicentre located about 32 km from the centre of the city [5]. Levelling and 3D laser scanning of the bell tower were repeated in the following months. We found no changes in the shape, but the two monitoring techniques were effective in highlighting the sudden movement of the foundation and axis produced by the earthquakes.

The purpose of this paper is to show how the two control techniques are able to integrate well following a different time rate, *i.e.* by repeating the high-precision levelling at short time intervals and the TLS at longer intervals or on the occasion of sudden events such as an earthquake when the change of axis inclination and of shape have achieved significant values for the accuracy of TLS.

2. Previous and recent monitoring of the bell tower of San Benedetto Church and detection of the secular movement

The bell tower of San Benedetto Church (Fig. 1) was built between 1621 and 1646; its design is traditionally attributed to

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(a) (b) (c)

Fig. 1. a: San Benedetto Church in Ferrara (Italy) and the bell tower; b: detail of the upper part of the tower and (c) its base.

G.B. Aleotti (1546–1636), architect at the court of the Dukes of Este. The masonry tower rises about 55 m.

It is not known when the tower began to lean, although it can be excluded that it occurred during its construction. In 1883, a plumb line was attached at the top of the north wall and the out of plumb of the whole building was calculated; as shown in Fig. 2d, an overhang of 2.50 m westward and 0.40 m northward was observed between two sections at a distance of 52.45 m, from the base of the marble block sustaining the cross (point C in Fig. 2b) to the ground. Unfortunately, no further control measurements were carried out from then until 2003 when the Department of Engineering, University of Ferrara carried out a new monitoring of the base of the tower by digital levelling alone. Since the measurements (2003–2008) showed that a significant settlement of the foundation was taking place, the position of the tower's axis was determined by TLS in 2008 to quantify the increase of axis inclination since 1883.

The control network realized in 2003 (Fig. 3a) consists of four benchmarks placed on the corners of the tower (C1, C2, C3, C4) and two reference benchmarks placed on the adjacent San Benedetto Church (C5, C6). Since 2003, the network has been surveyed at least once a year with a high-precision digital level with Invar-coded rod. For each survey, the network was adjusted by least squares method with benchmark C5 as reference point. Fifteen measurement campaigns were carried out from 2003 to 2011 (before the earthquakes). The maximum value of the standard deviation of the adjusted heights did not exceed 0.5 mm in any survey. The height variations of all the benchmarks in about nine years are shown in Fig. 3d (before the earthquake line). The height difference between the west (C1 and C2 −3.5 mm) and the east (C3 and C4 +0.7 mm) side of the base of the tower increased by 4.2 mm, about 0.49 mm/year (in 8.5 years), corresponding to an increase of the overhang of about 3.5 mm/year.

In 2008, a Leica HDS3000 laser scanner was used for the first time to reconstruct the present position of the tower's axis and to determine its overhang. A complete geometric model of the building was created in which three superimposed sections were identified (from the ground level to the bell chamber, the bell chamber, the upper chamber with the dome); this showed insignificant deviations of the geometric axis. Therefore a mean axis was defined as the straight line connecting the geometric centre C of the horizontal cross section at the base of the marble block supporting the top metal sphere (Fig. 4) to the analogous centre of the horizontal cross section resting 52.45 m below. Hence it was also possible to identify a virtual plumb-line in the model starting from point C in order to compare the present overhang with the one of 1883: the result was an overhang of 2.82 m and 0.50 m along the westward and northward directions respectively (Table 1). To confirm this result, a new TLS survey was performed with a Leica C10 laser scanner in 2011. The value of the overhang was recalculated from the virtual plumb-line: as shown in Table 1, the results of the 2008 survey were confirmed, with an increase of 3 cm only in the east-west direction.

Comparison of these overhang values with the historical data revealed a westward and northward increase of the overhang of 0.35 m and 0.10 m respectively. If for the sake of simplicity we assume a constant rotation velocity in the last 128 years, there has been an increase of the overhang of 2.7 mm/year and 0.8 mm/year in the westward and northward directions respectively. Nevertheless the assumption of a constant rotation velocity might be

Table 1
Overhang values in all the terrestrial laser scanning surveys.

Overhang [m]	2008	2011	2012	2013
East-west direction	2.82	2.85	2.88	2.88
North-south direction	0.50	0.50	0.51	0.51
Total	2.86	2.89	2.92	2.92