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Multisensor surveys of historical buildings before, during and after a seismic sequence: the leaning bell tower of Ficarolo (Rovigo)

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Three regions of Northern Italy (Emilia Romagna, Veneto and Lombardy) were struck in May-June 2012 by a seismic sequence that included a moment magnitude 5.9 earthquake. Such a sequence caused significant damage to several historical buildings; in some cases complete structural collapse occurred. The 69-m high bell tower of Ficarolo (Rovigo province, Northern Italy) leans at a significant angle ($\sim 3^{\circ}$ in the shaft). Because the combination of height and leaning angle is visually impressive, Ficarolo is also known as the "Pisa of Polesine" (Polesine is the Venetian bank of the Po River), referring to the well-known 55-m high, 4° leaning tower of Pisa. A project aimed at studying the geometry of the tower, by means of terrestrial laser scanning (TLS), possible local seismic amplification and soil-structure interaction (SSI), by means of low-cost operational modal analysis (OMA) and geophysical measurements, began in early 2012, before the earthquake. In particular, the first series of data were taken in February 2012 (OMA) and April 2012 (TLS).

The distance from Ficarolo of the epicenters of the six events with moment magnitude higher than 5.0 ranged from 9 km to 37 km. Several cracks appeared in the bell tower belfry and cusp. An inclinometer installed in 2003 showed that the base was unchanged, but the upper part of the shaft had moved by 2.5 cm after the main shock. No further displacements were detected as a result of the aftershocks.

The repetition of the TLS and OMA surveys during and after the seismic sequence, together with infrared thermal imaging (IRT) measurements, allowed an evaluation of the changes caused by the earthquake. Two main results were obtained: (1) an estimate of earthquake induced damage to the Ficarolo's bell tower, which were relatively limited thanks to absence of SSI, and (2) it was demonstrated that fast measurements can be repeated during earthquake emergencies and that preventive measures can be carried out under reasonable time and budget constraints in high seismic hazard areas. The second point is particularly important from the viewpoint of cultural heritage management purposes.