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HIGH AMPLITUDE FORCED OSCILLATIONS OF A MODERN BELL TOWER IN ROME

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ABSTRACT

Bell towers are typically high slender structures, usually attached to churches and city halls (*belfries*) or free standing near eminent civil and religious buildings (*campanili*). They represent important urbanistic emergencies in the whole Italian country, and the most famous and ancient masonry structures, dated to the early Middle Age (Leaning Tower of Pisa, St Mark's Campanile in Venice, Giotto's Bell Tower in Florence), constitute a rich cultural heritage, for their historical and architectural value. The major interest in bell towers is therefore focused on non destructive techniques for their health monitoring [1] or on intervention solutions for structural repairing and strengthening [2].

Bell towers are now rarely constructed, essentially since the bells sound has nowaday lost its ancient meaning of civil warning, and remains to signify the time for special religious events. Due to the present possibilities offered by technologies and materials, the modern bell towers are often characterized by audacious and spectacular architectural design, which require structural solutions driven by the research of extreme lightness and slenderness. In these constructions, rather than using heavy bells, the sound is commonly produced electronically and sounded through loudspeakers.

The *St. Patrick Campanile* in Rome (Figure 1a,b), built in the beginning of 2007, equipped with five massive bells, probably represents a unique chance to study the dynamical behaviour of a modern-designed bell tower under the excitation caused by the swinging bells. The tower structure, 20 *m* tall, made of reinforced concrete, behaves essentially as a vertical cantilever with variable section. The stiffness of the L-shaped section is strongly reduced at about one half of the total height to host the bells, which are suspended from horizontal rectangular steel frames, connected to the concrete structure.

The bell tower experienced high amplitude oscillations during service. In particular visual observations showed the top section to significantly oscillate under the motion of the two massive bells located at the highest positions (identified as b_4 and b_5). Therefore, a series of experimental tests were performed in May 2007. The tower was equipped with eight accelerometers, and its forced oscillations was recordered under ambient excitation and the bell motion. The maximum acceleration peak measured at the tower was around $0.23g$, due to the motion of the highest bell b_5 (Figure 1c, blue line). The data were treated to characterize the structural dynamical response through both frequency- and time-domain techniques. The results from the ambient excitation initially allowed the identification of the tower modal properties. Instead, the forcing frequencies of the bells were extracted from the tower response under the excitation furnished by each bell separately.

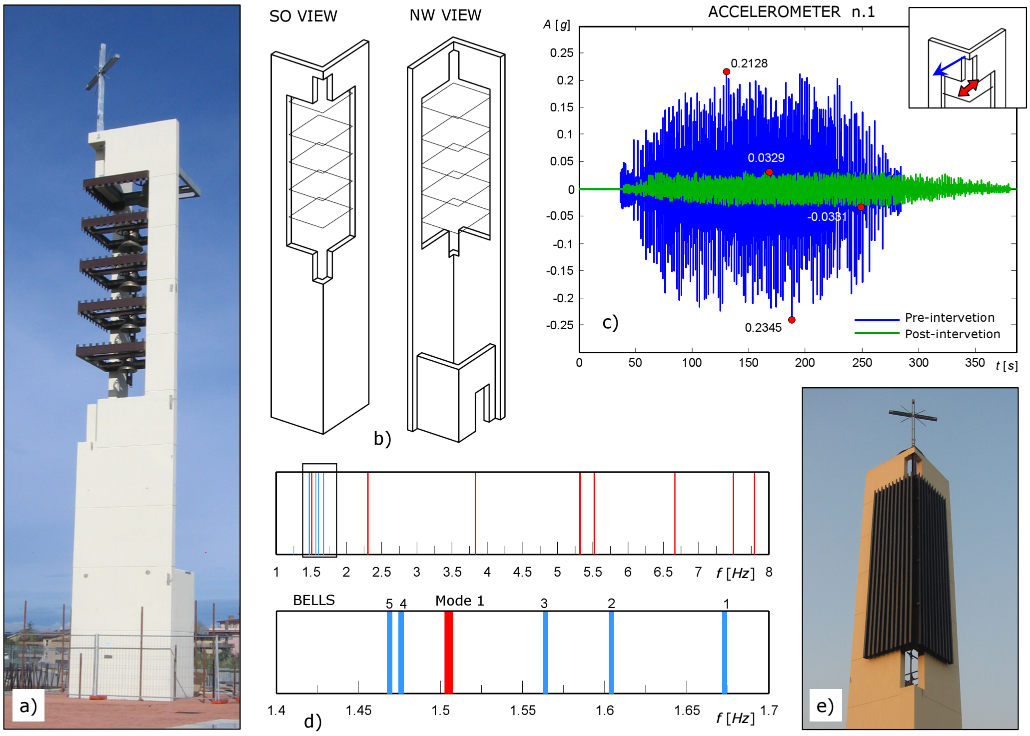

Figure 1: St. Patrick Campanile: pre-intervention (a) picture and (b) sketch, (c) tower top oscillations under the action of the highest bell b_5, (d) tower and bell frequency spectrum, (e) post-intervention picture.

A classic linear resonance between the first mode of the tower ($f_{t1} = 1.505\,Hz$) and the excitation frequency of the highest bells ($f_{b4} = 1.476\,Hz$, and $f_{b5} = 1.469\,Hz$) was found to be the source of the high amplitude tower oscillations (Figure 1d). A finite element model, once manually updated to match the experimental modal properties, has given qualitative and quantitative confirmations of the observed phenomenon.

The finite element model was also used to design a intervention aiming to modify the structural stiffness in order to recover the serviceability of the bell tower. The steel section of a vertical strut was on purpose dimensioned to stiffen the corner of the current L-shaped section (Figure 1e). The strut is verified to significantly enhance the dynamical behaviour of the tower, since a post-intervention series of experimental tests has shown a significant reduction of the oscillation level under the motion of the highest bells (Figure 1c, green line). The treatment of the registered data has confirmed that the presence of the strut efficiently modify the spectrum of the tower, since the first frequency increases of about 36% ($f_{t1} = 2.053\,Hz$), eliminating the resonance responsible of the excitation mechanism.

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