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Seismic assessment and retrofit of two heritage-listed R/C elevated water storage tanks

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ABSTRACT

A seismic assessment and advanced retrofit study on two heritage-listed reinforced concrete (R/C) elevated water storage tanks is presented in this paper. The two structures were built between the late 1920s and the early 1930s as water suppliers for a coal power plant in Santa Maria Novella Station in Florence, and are still in service. The first, taller tank has a R/C frame supporting structure and is currently used as water supplier for trains and platform services. The second, shorter tank, with a shaft-shell supporting structure, is used as water tower for the Station. The dynamic behaviour of the fluid is simulated by means of a classical convective and impulsive mass model, for which a discrete three-dimensional schematization is originally implemented in the finite element analysis. The time–history assessment enquiry highlights numerical collapse of the frame structure in the taller tank, and unsafe tensile stress states in a large portion of the shaft structure of the shorter one, under seismic action scaled at the maximum considered earthquake level. Based on these results, two retrofit hypotheses are proposed, and namely a dissipative bracing system incorporating pressurized fluid viscous spring-dampers, for the taller tank, and a base isolation system including double curved surface sliders, for the shorter one. The mechanical parameters, design criteria and technical implementation details of the two rehabilitation strategies are illustrated. The verification time–history analyses in protected conditions show that a substantial enhancement of the seismic response capacities of both structures is attained as compared to their original configurations, with little architectural intrusion, quick installation works and competitive costs.

1. Introduction

Water storage tanks represent strategic lifelines especially in earthquake-prone regions, for their essential role in fighting fires that often occur during severe seismic events, as well as in mitigating the consequences of water shortage resulting from damage to municipal aqueducts and pipelines, in the post-quake emergency phase. Water tanks have been traditionally built in elevated position over a supporting structure, so as to reach the pressurization required by the supply system simply by gravity, limiting the action of pumps to the refilling phase. As a consequence, elevated water tanks (hence their name of water towers) are normally rather tall and slender. This marks significant geometrical and structural differences with storage tanks for liquids of industrial use, such as oils, petroleum, nitrogen and liquefied natural gasses, most of which are broad in plan and ground-supported (or at most mounted over a short staging, as in the case of spherical vessels).

The supporting structure of elevated tanks, mainly constituted by pre-normative R/C frames or R/C (or masonry) shaft-type shells, and in few cases by steel braced frames, is generally the weakest portion of the structural system, which determines a high seismic vulnerability of these facilities. This is also demonstrated by severe damages and collapses suffered by elevated tanks in past and recent earthquakes [1–3]. Another peculiar hazard is represented by the fact that, unlike industrial liquid tanks, water towers are often situated in urban areas, and even in city centres; therefore, their partial or global failure can cause heavy damages to the surrounding buildings and infrastructures, with serious consequences for the safety of a great number of inhabitants. At the same time, many old water towers are now considered historically significant and have been included in the heritage listings of several earthquake-prone countries. This imposes their preservation and possible seismic retrofit by means of low impact structural solutions, respectful of their recognised architectural and engineering value.

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Fig. 1. Photographic view of the two tanks before the construction of the encasing masonry building (in 1935) and current views of the latter from the same and the opposite viewpoint.

In view of this, the class of advanced earthquake protection technologies based on the dual concepts of seismic isolation and supplemental damping [4] can offer effective rehabilitation solutions for these special structures too. However, whereas several studies have been dedicated to the seismic isolation of ground-supported tanks, and some actual applications have been recently noticed [5–8], few references on isolation-based [9,10] or supplemental damping-based [8,11,12] retrofit designs of elevated tanks are found in the literature. Hence, a research programme aimed at extending to this field the use of both types of rehabilitation strategies, deeply enquired by the second and third author for building structures, was recently undertaken.

A first representative case study examined within this research, consisting of two adjacent heritage water tanks supported by a R/C frame and a R/C shaft structure, respectively, is reported in this paper. The frame-supported tank, named "tall tank" in the following, is 21.6 m high, with staging and vessel heights of 15 m and 6.6 m; the shaft-supported tank, named "short tank", is 12.3 m high, with heights of the two portions equal to 6.5 m and 5.8 m. The two structures were built between the late 1920s (short tank) and early 1930s (tall tank) as water suppliers for a coal power plant in Santa Maria Novella Station in Florence, and are still in service. The vessels are among the first Intze-type realizations in Italy, constituted by two thin coaxial R/C cylindrical walls, the inner of which houses a manhole. The R/C vessels are completed by external inverted truncated cone floor slabs and internal cylindrical (short tank) or conical (tall) floor slabs, bottom and top ring beams, a cylindrical (short) or conical (tall) roof slabs, and cylindrical lanterns on top, with conical (short) or flat (tall) roofs, for vessel aeration and natural illumination. One year after the completion of the tall tank, designed by the world-famous Italian engineer Pier Luigi Nervi, the two structures were encased in a brick masonry building, constituted by two semi-cylindrical wings enveloping the geometry of the tanks, and a central parallelepiped-shaped connecting wing. The only horizontal elements of the masonry structure are lower and upper thin R/C roof slabs, situated immediately over the top of the short and the tall tank, respectively. The enveloping masonry building, structurally independent from the water towers, was added to better integrate them, from an aesthetical viewpoint, with the other technical buildings and facilities belonging to the railway park of Santa Maria Novella Station – all designed by architect-engineer Angiolo Mazzoni – as well as with the monumental passenger building, designed by architect Giovanni Michelucci and Associates, considered as the masterpiece of Italian Rationalist architecture. The resulting "water supplier building" constituted by the two elevated tanks and the masonry enveloping structure, is now listed as modern heritage architecture by the Florentine Superintendence to Fine Arts. A photographic view of the two tanks showing their appearance in 1935, before the construction of the encasing masonry building, and current views of the latter taken from the same and the opposite viewpoint, are displayed in Fig. 1.

Like for other similar water towers situated in urban areas, high seismic hazard is related to the severe damage or partial/total collapse of the two tanks, in this case accentuated by their critical location in proximity to tracks and passenger platforms, on one side, and office and service buildings, on the other side. Furthermore, an additional peculiar hazard is represented by the presence of the encasing masonry structure. Indeed, in spite of the satisfactory seismic performance capability of the latter due to the minimal gravity loads supported (the own weight of the walls plus the two thin roof R/C slabs only), the collapse of portions, or complete loss of stability, of the two tanks would cause collisions with the masonry walls, which in turn could crash on the railway tracks or the surrounding buildings.

In order to assess the seismic performance of the two water towers via finite element time–history analysis, the dynamic behaviour of the fluid is simulated in this study by a three-dimensional assembly of the convective plus impulsive spring-mass model originally proposed by Housner [13], illustrated in the next section. The results of the numerical enquiry show an extremely high plastic demand on the frame structure of the tall tank, determining its numerical collapse, and unsafe tensile stress states in a large portion of the shaft structure of the short tank, under seismic action scaled at the maximum considered earthquake (MCE) level. Based on these data and the structural characteristics of the water towers, two distinct retrofit hypotheses are then proposed, consisting in the installation of a dissipative bracing system incorporating pressurized fluid viscous spring-dampers, for the tall tank, and a base isolation system including double curved surface sliders, for the short one. The mechanical parameters and technical implementation details of the two protective systems, and the benefits induced in the seismic response of the water towers are discussed in the final section, by comparisons with the performance of the two structures in original conditions.