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Derivation of floor acceleration spectra for an industrial liquid tank supporting structure with braced frame systems

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ABSTRACT

Past seismic events have shown that industrial facilities may suffer greatly from earthquake-induced actions, which can cause simultaneous damages to different key apparatus, initiating major/multiple accidental chains. Therefore, the evaluation of seismic demand acting upon structural systems and equipment is of utmost importance when assessing or designing a complex industrial plant, which will be inevitably exposed to seismic hazards during its lifetime. Furthermore, it is noteworthy that, if modern seismic design procedures are able to successfully limit damage to the main structural elements, the evaluation of secondary structural and non-structural components may imply less trivial considerations because of the important role played by them (e.g. storage of chemical/hazardous substances) and the lack of accurate code-compliant approaches applicable to each specific case.

As such, this paper is chiefly concerned with the derivation of floor acceleration spectra for a special concentrically braced frame supporting a cylindrical storage tank, the latter being a basic strategic component widely used in several industrial applications and the former one being one of the most common forms of lateral-force resisting systems for plant structures. Firstly, a fibre-based finite element model of the supporting frame itself was developed within an open source platform and then nonlinear time history analyses were performed assuming a set of 47 natural ground motions scaled to 8 seismic intensities. These results, used to assess the tank as an uncoupled system, were additionally compared with those obtained by a second analysis run, in which the interaction between the supporting structure and the tank was explicitly accounted for by modelling them together. A well-known analytical model, consisting of two uncoupled single degree of freedom systems for the impulsive and convective components of motion, was considered in this case to reproduce the response of the tank. The floor spectra resulting from these two approaches were compared together so as to quantify trends and differences in the observed estimates. Sensitivity to the viscous damping was examined as well. A comparison was finally derived between the nonlinear dynamic analyses of both coupled and uncoupled systems and the analytical methods of current Codes (ASCE 7-10, EC8) and recent research proposals.

1. Introduction

Storage systems, such as cylindrical steel tanks and horizontal/vertical vessels, play an important role in the correct functioning of a process plant, since raw or refined materials, often inflammable and/or pollutant, are contained using many of these items, each of which is allocated in a specific unit of the plant. Needless to say that the accidental release of chemicals in the environment could produce a number of casualties and health impacts/changes resulting from exposure to the toxic cloud, as well as serious indirect/economic losses. For this reason, these equipment have to be designed to ensure safety against any low probability-high consequence event that may occur in the lifetime of the plant, and earthquakes are one of the most vivid examples of this type of occurrence. Both observations of damage in the aftermath of major/moderate seismic events [1–10] and numerical or experimental studies undertaken to explore the seismic behaviour of typical structural systems and components [10–21] have reaffirmed that industrial facilities are particularly and in some cases even disproportionately vulnerable to earthquakes. Furthermore, whilst accidents caused by other internal events often occur in a specific portion of a specific unit of the plant, simultaneous occurrences might take place during an intense earthquake and damage might propagate as a sort of cascade or domino effect [12,22,23]. This is mainly due to the fact that, unlike common buildings, industrial facilities and installations are complex

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systems composed of a vast variety of structures, sub-structures, and secondary or non-structural components, regardless of whether chemical, petrochemical, or food processing industries are concerned.

Given that process activities are most likely carried out in series, the elements/items of a plant are arranged accordingly, which in turn implies that damage/failure of a single component may affect the integrity of the entire system, leading to severe consequences other than business interruption. To avoid this, redundant safety systems are specifically conceived and usually installed in industrial plants, mitigating the impact of a component failure. Apart from downtimes, the loss of containment (e.g. oil, nitrogen, or high-pressure gas) may result in triggering of life threatening accidents (e.g. fires or explosions), overload/depletion of emergency services or life sustaining materials, and irreparable environmental pollution. If the nearby areas are populated, densely or not, a cascading spill of hazardous substances contaminating the soil and the water supply would affect inhabitants with health changes that may become clinically evident even months or years after the event. Therefore, safety conditions of equipment and installations against dangerous events, like earthquakes, are of paramount importance.

Typical industrial configurations are modular and are often made of storage systems and pipes resting on steel racks or special/ordinary braced frames, whose seismic response could be influenced by the dynamic coupling between the supporting structure and the supported items. Thus, in evaluating the safety conditions of a tank/vessel under coupled conditions (supporting structure + tank/vessel), it is essential to focus on the influence that the coupling effects may have on the response of the latter element, particularly for strong dynamic actions. Concerning this point a few indications have been provided so far in seismic codes (e.g. ASCE 7-10 [24] and Eurocode 8, namely EC8 [25]) and the evaluation of the behaviour of a frame-tank system is still an open issue, as is also the evaluation of the seismic demand acting upon the supported storage system.

In this respect, floor acceleration/displacement spectra are a viable and promising approach, which however has been applied to a lesser extent to the case of industrial/plant structures. Indeed, besides a relatively large number of studies on non-structural components/elements for buildings [26–39], contributions dealing with the derivation of floor response spectra for this type of applications are quite limited [11–13]. It is also worthwhile to mention that the consistency and suitability of expressions proposed in building codes, such as ASCE 7-10 [24] and EC8 [25] are questionable, as pointed out by many researches working on building structures [26–30,34]. These code-compliant formulae for the determination of floor spectra neither consider damping of the secondary elements nor differentiate between elastic and inelastic behaviour of the primary structure. They turned out to be oversimplified and inaccurate, which possibly makes them even more unsuitable for structures pertaining to industrial plants, as discussed later on in the paper by means of a comparative analysis.

Thus, a number of researchers have extensively highlighted the shortcomings of codes, discussing the influence of non-structural damping, nonlinearity of the supporting structure and dynamic coupling for supporting systems that include reinforced concrete and steel frames and reinforced concrete shear walls, amongst others (see e.g. [26–29,34,35,38]). On the other hand, examples of direct analysis, in which whole systems composed of primary structure and non-structural components are modelled and analysed together, have appeared in the literature [40]. Although this approach is clearly more time-consuming, it fully accounts for the complex dynamic interaction between primary and secondary systems through time, and thus is the most accurate and desirable method for this type of critical/strategic structures. Furthermore, a series of analytical approaches have been proposed to estimate the floor spectra, and more generally, the seismic demand on non-structural elements. A few examples include the work of Sullivan et al. [26], Calvi and Sullivan [28], Calvi [29], Welch [35] and the proposals of Vukobratovic and Fajfar [34,38].

In light of this scenario, a case study special concentrically braced frame (SCBF) supporting a cylindrical storage steel tank was selected and designed according to the prescriptions of AISC 360-10 [41] and AISC 341-10 [42]. After validation against experimental data available in the literature [43], numerical techniques able to reproduce the cyclic response of bracing systems and gusset plates were included in a fibre-based finite element (FE) model of the reference structure. A wide set of nonlinear time history analyses (NLTHAs) was then carried out by making use of 47 natural accelerograms scaled to 8 seismic intensities, which allowed derivation of floor acceleration spectra on the basis of the results of the primary structure studied as an uncoupled system. Furthermore, the dynamic interaction between the supporting SCBF structure and the tank was explicitly taken into account, as an additional mechanical model was integrated within this computational framework in order to simulate the behaviour of the storage system. More in detail, the approach proposed by Malhotra [44,45] and codified in the EC8 Part 4 – Annex A [46] was assumed for this second analysis run, in which the effects of impulsive and convective components of motion are included through the implementation of two uncoupled single degree of freedom (SDoF) systems. Trends were examined, and a twofold comparison was provided between the floor spectra obtained (i) by different techniques for the same seismic intensity, and (ii) by each one of the two analysis methods for increasing levels of seismic intensity. The floor spectra resulting from the nonlinear dynamic analyses of both coupled and uncoupled systems, for the seismic intensity assumed at the design stage, were finally compared with those computed in accordance with analytical code-conforming formulae [24,25] and research proposals [26,28,34,35,38]. The abovementioned approaches – direct analysis, indirect analysis, ASCE 7-10 [24], EC8 [25], Sullivan et al. [26], Calvi and Sullivan [28], Vukobratovic and Fajfar [34], Welch [35], and Vukobratovic and Fajfar [38] – are also compared in terms of maximum shear force and overturning moment acting upon the tank.

2. Description of the case study industrial frame-tank system

2.1. Special concentrically braced frame

A 5-story, 3-bay planar SCBF structure, which resembles bay and height dimensions common for industrial steel frames, was selected and studied in this research work. It is worth noticing that the chosen geometrical layout, in terms of span lengths and inter-storey heights, was taken from a more complex three-dimensional structure supporting a piping system with elbows, Tee and flange joints that was analysed and tested by Bursi et al. [15,16].

The framing elements, as well as the bracing system consisting of square hollow structural steel (HSS) braces and welded gusset plates, were sized according to a classical force-based design procedure and the requirements implemented in US provisions [24,41,42]. Standard American profiles were used accordingly. The lateral seismic forces were calculated in accordance with the mass distribution discussed later on, applying the prescriptions given by ASCE 7-10 [24]. The 5% damped elastic design spectrum, along with the main design parameters, is presented in Fig. 1. In particular, R is the response modification coefficient, which is equal to 6 for a SCBF system, and I_e is the seismic importance factor, which takes a value of 1.25 for Risk Category III. It is should be emphasised that the aforementioned risk category is described within ASCE 7-10 [24] as “buildings and other structures, the failure of which could pose a substantial risk to human life”. Since damage/failure of any part of an industrial facility can clearly pose detrimental consequences to human life and/or the environment, this risk category was considered for design of the structure and all its components. Furthermore, it is noteworthy that the equivalent viscous damping for the elastic design spectrum was set to 5% in line with ASCE 7-10 [24] (see clause 9.4.1.3.1), as well as EC8 [25] (clause 3.2.2.2), although lower values may be selected for items belonging to nuclear