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Seismic response mitigation of chemical plant components by passive control techniques

F. Paolacci [a,*], R. Giannini [a], M. De Angelis [b]

[a] Department of Structures, University Roma Tre, Via Corrado Segre 00146, Rome, Italy
[b] Department of Struct. and Geotech. Engineering, University of Rome "La Sapienza", via Eudossiana 18, 00184 Rome, Italy

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ABSTRACT

This paper deals with the applicability of seismic passive control in major-hazard chemical installations. The objective is to show numerically and experimentally the applicability of Passive Control Techniques (PCT) in industrial plants. Consequently, the main components of a process plant are classified and collected into a limited number of classes; for each class, the main damages caused by past earthquakes are described and the most vulnerable components are identified. A synthesis of the effects of earthquakes on the different typologies of process components is also presented and the most suitable innovative seismic protection systems, in particular passive control techniques (PCT), are acknowledged. Finally, the effectiveness of PCT in reducing the seismic response of process plant components is proved by three representative case studies: a base isolated above-ground storage tank, a distillation column connected by elastoplastic dampers to the adjacent service frame and an application of non-conventional Tuned Mass Dampers to a support frame.

1. Introduction

The current worldwide situation of industry concerning natural events, e.g. earthquakes, is particularly critical. This is clearly demonstrated by the consequences of serious accidents caused by natural events to industrial plants (Na-Tech events), particularly in the chemical and oil processing industries. Consequences include the release of the hazardous materials (fires, explosions), human injuries and the increasing of overall damage to nearby areas, proving this to be a key emerging risk issue (Cozzani, Campedel, Renni, & Krausmann, 2010; Krausmann, Cozzani, Salzano, & Renni, 2011; Talaslidisa et al., 2004; Young, Balluz, & Malilay, 2005). In fact, chemical accidents triggered by natural events like earthquakes have been recognized to be the cause of about 5% of accidents with the release of hazardous substances (Campedel, 2008). Earthquakes can cause severe damages to industrial plants, initiating major accidents, as clearly shown in several events (Hatayama, 2008; Krausmann, Cruz, & Affeltranger, 2010; Moat, Morrison, & Wong, 2000; Nishi, 2012; Sezen & Whittaker, 2006; Suzuki, 2006). The main reason is that chemical plants are complex systems, and this complexity, due to numerous connections and components renders them particularly vulnerable to earthquakes. In fact, in the case of a seismic event, the earthquake can induce simultaneous damages to different apparatus, whose effects can be amplified because of the failure of safety systems or the simultaneous generation of multiple accidental chains. In addition, activities carried out in process plants are often arranged in series. Consequently, the "failure" of a single element may result in the "failure" of the entire system.

In a chemical plant, an earthquake can cause many human losses as a consequence of component collapses, similarly to buildings, along with indirect effects such as economic losses, downtimes, environmental damages due to releases of dangerous substances, damages due to explosions, fires and the release of toxic substances. Therefore, the usual safety requirements applied to civil buildings for ultimate and serviceability limit states and the consequences of exceptional actions are generally unsuitable for structures belonging to industrial plants. As a matter of fact, critical damages that could cause even a modest release of inflammable substances, such as a flange opening or a welding breaking, can result insignificant from a structural point of view, but, at the same time, might cause considerable accidental chains. Consequently, for process industry it is unavoidable to associate indirect consequences of accidents due to seismic events to direct structural damages. Therefore, many authors have suggested methodologies for a quantitative risk analysis (QRA) of the main chemical plant components for the calculation of their fragility curves and risk indexes, useful for the assessment of possible reference scenarios

* Corresponding author. Tel.: +39 0657336418.
E-mail addresses: paolacci@uniroma3.it (F. Paolacci), giannini@uniroma3.it (R. Giannini), maurizio.deangelis@uniroma1.it (M. De Angelis).

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triggered by seismic events (Antonioni, Spadoni, & Cozzani, 2007; Campedel, Cozzani, Garcia-Agreda, & Salzano, 2008; Fabbrocino, Iervolino, Orlando, & Salzano, 2005; Korkmaz, Ali Sari, Asuman, & Carhoglu, 2011; Salzano, Iervolino, & Fabbrocino, 2003). They have shown the general high vulnerability of chemical plant components and the need for suitable protection systems e.g. Early Warning (EW) (Salzano, Agreda, Carluccio, & Fabbrocino, 2009). An EW system activates interlock systems and fast shut-off valves to prevent loss of content and consequent accidents.

A different solution is represented by passive control techniques (PCT). They have been developed during the last 40 years and are based on the concept of reducing the seismic action instead of increasing the structural strength (Spencer & Nagarajaiah, 2003). For civil constructions, these techniques are nowadays considered a consolidated alternative design tool for new or existing structures in seismic-prone areas. Unfortunately, PCT is not easily applicable to industrial structures, for at least two reasons: 1) the large variety of structural and geometric configurations of plant components, 2) the different design objectives and working conditions, closely related to the consequences of possible accidents.

As a matter of fact, until now, PCT have been used for a very limited number of industrial applications; for example, in Europe the isolation technique has been adopted only in a few cases: the seismic protection of Petrochemical LNG terminal of Revythousa, Greece (Tajirian, 1998) and of ammoniac tanks, at Visp, in Switzerland, by means of elastomeric isolators (Marioni, 1998). Friction Pendulum devices were also used for the seismic isolation of an elevated steel storage tank of the petrochemical plant of Priolo Gargallo in Sicily (Italy) (Santagelo, Scibilia, & Stadarelli, 2007). In Korea a couple of LNG tanks have been isolated using high damping rubber bearings (Koh, 1997). Two large liquefied natural gas (LNG) tanks for the Melchorita facility (Perù) have been seismically protected with Triple Pendulum bearings. The facility is located in an area with high seismic hazard. Use of seismic isolation in these LNG tanks resulted in an economical tank design with a reduced footprint, while providing the most reliable mechanism for accommodating the large seismic displacements that occur during an earthquake.

Nevertheless, analytical and experimental tests have clearly demonstrated the effectiveness of isolators in reducing the response of storage tanks (Calugaru and Mahin 2009; Chalhoub & Kelly, 1990; De Angelis, Giannini, & Paolacci, 2010). Other applications of PCT to industrial components have been proposed in the past for the seismic protection of piping systems using yielding or friction-based bearings (Bakre, Jangid, & Reddy, 2004), or semi-active dampers (Kumar, Jangid, & Reddy, 2012). For this reason, in the present paper the use of PCT is investigated, aiming at providing general applicability criteria. In particular, after a historical survey of the structural behavior and the relevant damages suffered by oil refinery components during strong earthquakes, a structural classification of the analyzed components is provided and an overview on the most suitable protection strategies, based on passive control techniques, are proposed for each of the recognized structural categories.

Although the identification of the most important damage states was already provided in literature, especially to identify possible loss of content (LOC) phenomena and consequences, this paper concerns the same issue but with a particular attention paid to structural aspects only; the goal is to explain the close relationship between structural typology and passive control technologies (base isolation, energy dissipation, TMD, etc.). In addition, some qualitative information on how PCT can help in avoiding possible hazard accidents is provided and discussed, leaving the identification of the relationship between the structural and hazard benefits provided by PCT systems to further works. Thus, the main objective of the paper is to show numerically and experimentally the applicability of PCT in industrial plants; these results could be profitably used for a further quantitative evaluation of the seismic risk of a plant in presence of response mitigation systems.

In order to demonstrate the effectiveness of the suggested PCT solutions (isolation, energy dissipation and TMD) in reducing the seismic response of refinery components, the following three case studies are analyzed and discussed in the final part of the work: a) the design of base isolation systems for the seismic protection of above-ground steel storage tanks, b) the applicability of dissipative coupling technique to reduce the seismic response of a service frame and a distillation column belonging to a thermal cracking plant of a refinery, c) the application of non-conventional TMD technique to a service frame.

2. Seismic behavior of oil refinery components

Despite different targets, which entail a large variety of plants with a large variety of configurations, process industry utilizes common basic operations and consequently similar equipment and systems that can be collected in a limited number of structural typologies (Paolacci, Giannini, & De Angelis, 2012; Salzano et al., 2009).

During transformation processes many dangerous substances are treated. Consequently, a refinery is equipped with numerous safety systems. It is worthwhile to highlight that during a seismic event they could fail, becoming useless. This suggests that the seismic protection of a refinery must be mainly based on the reduction of the seismic response of the single component.

The experiences derived from the observation of damages caused to industrial plants by past earthquakes can be very useful in identify the most vulnerable components to seismic action and the evaluation of the consequences. In spite of the difficulties in obtaining and organizing data, detailed information on the behavior of refineries in a certain number of earthquakes is available in certified databases (ICHEME, 2004; MARS, 2006; MHIDAS, 2001;). Based on this information, in the following, the main equipment of process plants is grouped into a restricted number of structural classes and the main damages observed during earthquakes are analyzed. According to Table 1 the following structural classes are acknowledged:

- Slim vessels
- Above-ground squat equipment
- Squat equipment supported by column
- Piping systems
- Support structures

The first category includes mainly cylindrical vessels and can be subdivided in two sub-categories: vertical cylindrical vessels (reactors, stacks and flares) and horizontal cylindrical vessels (pressurized storage tanks and heat exchangers). The main point of concern for slim vessels is the various transition zones, i.e. the connection between shell and skirt, and the connection to the foundation. Vertical vessels have experienced yielding and partial pull-out of anchor bolts (Ballantyne, ORourke, Krinitzsky, & Ellis, 1991; Stepp et al., 1990). These limit states have already been acknowledged and used for the evaluation of the seismic vulnerability of tall columns (Nielsen, Kiremidjian, & Burke, 1988), which proved their high probability of occurrence, even if bolts-yielding seems to be the most common. Horizontal vessels have similar problems at the connection with supporting pedestal and recent analytical studies have shown their non-negligible seismic vulnerability (Di Carluccio, Fabbrocino, Salzano, & Manfredi, 2008). For this category important LOC consequences have been