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Performance-based earthquake evaluation of a full-scale petrochemical piping system

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A B S T R A C T

Assessment of seismic vulnerability of industrial petrochemical and oil & gas piping systems can be performed, beyond analytical tools, through experimental testing as well. Along this line, this paper describes an experimental test campaign carried out on a full-scale piping system in order to assess its seismic behaviour. In particular, a typical industrial piping system, containing several critical components, such as elbows, a bolted flange joint and a Tee joint, was tested under different levels of realistic earthquake loading. They corresponded to serviceability and ultimate limit states for support structures as suggested by modern performance-based earthquake engineering standards. The so called hybrid simulation techniques namely, pseudo-dynamic and real time testing with dynamic substructuring, were adopted to perform seismic tests. Experimental results displayed a favourable performance of the piping system and its components; they remained below their yielding, allowable stress and allowable strain limits without any leakage even at the Near Collapse Limit State condition for the support structure. Moreover, the favourable comparison between experimental and numerical results, proved the validity of the proposed hybrid techniques alternative to shaking table tests.

1. Introduction

1.1. Background and motivation

In many industries, e.g., petrochemical, oil & gas and nuclear plants, piping systems play a major role by transferring raw and refined materials, such as oil and gas, from a location to another, often spanning hundreds of miles. Because a single or few failures might trigger serious accidental chains, special attention must be paid to ensure their safe and unhindered operations. This is clearly demonstrated by the consequences of serious accidents in industrial plants (Na-Tech events) caused by natural events, particularly in the chemical and oil processing industry. Consequences include the release of hazardous materials, human injuries and the increasing of overall damage to nearby areas, proving this to be a key emerging risk issue. In this respect, see Young et al. (2005), Cozzani, et al. (2010) and Krausmann et al. (2011). In particular, chemical accidents triggered by natural events like earthquakes have been recognized to be the cause of about 5% of accidents characterized by the release of hazardous substances (Campedel, 2008).

Nevertheless, such systems have been found to be highly vulnerable to seismic events. Significant damages in industrial piping systems and their components during past earthquakes have been reported which caused severe consequences to environment, economy and human lives (Sezen and Whittaker, 2006; Krausmann et al., 2010). This suggested researchers to conduct seismic performance evaluation of these systems/components; see, for example, Touboul et al. (1999), Reza et al. (2014). Other researchers start employed modern concepts of passive control or wireless sensor networks for monitoring and protection of process plants (Paolacci et al., 2013a; Rao et al., 2012). However, until now few experimental investigations – mainly through shaking table tests – have been performed on full-scale structures under realistic seismic loading; see, DeGrassi et al. (2008), Otani et al. (2011) and Nakamura (2013). All these tests displayed a favourable performance of piping systems which remained below yield limits under design level earthquakes; failure of supports or connections to

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List of abbreviations

CB	Craig–Bampton
CLS	Collapse Limit State
CM	continuous model
DLS	Damage Limit State
DLST	Damage Limit State Test
DoF	degree of freedom
DS	dynamic substructuring
EB	Euler–Bernoulli
ET	elastic test
FE	finite element
IDT	identification test
MCER	risk-adjusted maximum considered earthquake
NCLS	Near Collapse Limit State
NCLST	Near Collapse Limit State Test
NEE	normalized energy error
NRMSE	normalized root mean square error
NS	numerical substructure
OBE	operating basis earthquake
OLS	Operational Limit State
OLST	Operational Limit State Test
PBEE	performance-based earthquake engineering
PDT	pseudo-dynamic tests
PGA	peak ground acceleration
PS	physical substructure
RM	reference model
RT	real time tests
SLLS	Safe Life Limit State
SLLST	Safe Life Limit State Test
SSE	safe shutdown earthquake

other linked components occurred prior to the failure of the pipe itself. Other authors confirmed an over-conservativeness of relevant design standards; see, among others, Touboul et al. (2006), Paolacci et al. (2011, 2013b), Hosseinzadeh et al. (2013) and Nakamura (2013). Hence, a need for deep numerical and experimental investigations of piping systems and support structures under realistic seismic loading is evident. As a result, valuable information, such as seismic capacity and demand under different limit states, could be utilized for the amendment of relevant design Codes and Standards.

Along this line, an experimental test campaign based on hybrid simulations, i.e. pseudo-dynamic (PDT) and real-time tests (RT) with dynamic substructuring (DS), of a typical full-scale industrial piping system was undertaken. In greater detail, a number of hybrid tests were carried out on this system under several limit states of the support structure, suggested by modern performance-based earthquake engineering (PBEE) standards. PDT and RT (Shing et al., 1996; Bursi et al., 2008, 2011) are recent experimental techniques alternative and less expensive than shaking table tests, in which the overall response of a structure is evaluated by combining the experimental response of a physical substructure (PS) — which is generally the most critical part of the structure — with the numerical response of a numerical substructure (NS). Moreover, neither of these techniques needs to filter the low frequencies of the seismic input which are very detrimental to the displacement capacities of shaking tables. The main difference between a PDT and an RT is the rate of execution of an experiment; an RT is carried out in the actual time scale of an earthquake, whereas, a PDT is carried out in an extended time scale. However, because strain-rate dependent effects can practically be neglected for steel components, for frequencies of some ten of Hz (Tanaka, 2012), by means of experimental measurements of restoring forces combined with numerical evaluations of other contributions, the PDT method can reproduce the actual response of piping systems and support structures under dynamic/earthquake loading.

1.2. Scope

This paper focusses on the aforementioned test program and relevant results. Initially, finite element (FE) analysis of a typical piping system on a support structure subjected to seismic loading is described. FE modelling of the piping network, and in particular the critical elbow elements, is discussed in detail. Because, divergence stability and relevant dynamics caused by internal flow conveyed by pipes are not of interest, standard interpolation functions for FEs suffice (Lee et al., 2009). Moreover, the lack of guidelines for the

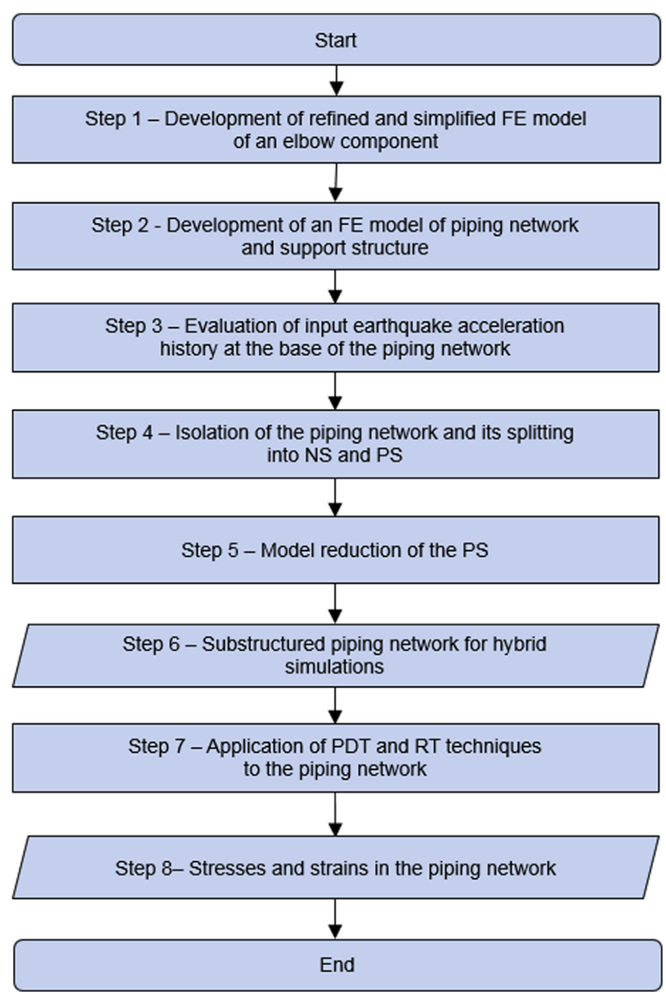

Fig. 1. Conceptual step sequence used to perform stress and strain checks on the piping system.