International Journal of Pressure Vessels and Piping 166 (2018) 61–71

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Effect of cyclic loading protocols on the experimental seismic performance evaluation of suspended piping restraint installations

Andre Filiatrault[a,b,*], Daniele Perrone[a], Emanuele Brunesi[c], Clemens Beiter[d], Roberto Piccinin[e]

[a] University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria n.15, 27100, Pavia, Italy
[b] State University of New York at Buffalo, Buffalo, NY, USA
[c] European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Adolfo Ferrata,1, 27100, Pavia, Italy
[d] Business Unit Installation Systems, Hilti Corporation, 9494, Schaan, Liechtenstein
[e] Hilti Corporation, 9494, Schaan, Liechtenstein

ARTICLE INFO

Keywords:
Loading protocol
Non-structural elements
Seismic
Suspended piping
Restrain

ABSTRACT

Suspended non-structural elements, such as water and sprinkler piping systems, are key to the functionality of important facilities, such as hospitals and schools. Recent earthquakes have demonstrated the vulnerability of these systems, particularly for those that were inadequately restrained. Seismic qualification requirements of non-structural elements contained in recent building codes and industry standards rely on experimental procedures, such as quasi-static cyclic testing of components and sub-assemblies. When conducting such quasi-static testing, the question arises as to what proper loading protocol to use. The first part of this paper reviews and compare existing cyclic loading protocols for testing various types of components and sub-assembles and developed according to scientific methods, including two specifically developed for testing non-structural elements. These two non-structural loading protocols are then used for conducting quasi-static cyclic testing of common components part of piping restraint installations. Characteristic response parameters resulting from test results with each cyclic loading protocol are extracted and compared. Observations and recommendations are provided on the effects of using different cyclic loading protocols for the performance evaluation and seismic qualification testing of suspended piping restraint installations.

1. Introduction

Suspended piping systems (water distribution and circulation, sprinkler systems, etc.) represent one of the key non-structural elements that ensure the functionality and safety of critical facilities, such as hospitals and schools. Piping systems in a building are primarily designed to achieve appropriate water pressure and flow, and to avoid contamination to potable water. The geometric configuration of piping systems largely follows room layout and is based on code compliances, building users' comfort, and sustainability. Typically, none of these design considerations involves seismic performance. Recent earthquakes worldwide have demonstrated the vulnerability and sometimes poor performance of suspended piping systems, which has caused a wide range of damage resulting in substantial property loss, loss of building functionality, as well as posing a significant hazard for potential fire spread and loss of life.

During recent major earthquakes, such as the 1994 Northridge earthquake in California, non-structural elements and systems installed with proper bracing systems according to current building code requirements generally performed well, with the exception of suspended water piping and fire sprinkler systems. Leakage and water damage resulting from suspended fire sprinkler and water supply piping systems forced the temporary evacuation of a number of buildings following the Northridge earthquake [18]. At least 13 hospitals suffered a wide range of water damage caused by the failures of piping joints [4]. The 2006 Kiholo Bay, Hawaii Earthquake is another example where functionality of critical facilities was impaired by the failure of suspended piping systems. Although schools and healthcare facilities sustained little structural damage during the ground shaking, they were not operational for weeks following the earthquake because of substantial damage to the non-structural systems. Besides non-structural failures such as fallen ceilings and light fixtures, damage to suspended fire sprinkler and water supply systems was also found to be one of the primary causes that led to the evacuation of the Kona Community Hospital [6].

* Corresponding author. University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria n.15, 27100 Pavia, Italy.
E-mail addresses: andre.filiatrault@iusspavia.it (A. Filiatrault), daniele.perrone@iusspavia.it (D. Perrone), emanuele.brunesi@eucentre.it (E. Brunesi), clemens.beiter@hilti.com (C. Beiter), Roberto.Piccinin@hilti.com (R. Piccinin).

https://doi.org/10.1016/j.ijpvp.2018.08.004
Received 10 July 2017; Received in revised form 18 August 2018; Accepted 18 August 2018
Available online 21 August 2018

During the 2010 Chile earthquake, four hospitals in the central south region of the country were rendered inoperable, and 12 hospitals lost almost 75% of their functionalities due to failures of non-structural elements including suspended fire sprinkler and water piping systems [13,16].

To address the repeated damage to non-structural elements, building codes have progressively increased their scope and strictness of their seismic design provisions for non-structural elements in an attempt to achieve better performance. In the last three decades, several government agencies and industry groups have also developed and implemented guidelines and standards for the seismic evaluation and retrofit of non-structural elements. Some recent codes and standards e.g. Refs. [1,9] rely on experimental seismic qualification procedures to establish the performance of non-structural elements. For suspended piping systems, experimental seismic qualifications are usually conducted through quasi-static seismic testing of restrain components or sub-assemblies [9]. When conducting such quasi-static testing, the question arises as to what proper loading protocol to use.

The main objective of this paper is to evaluate the influence of quasi-static cyclic loading protocols on the seismic performance evaluation of suspended piping restrain installations. The effects of loading protocol has been studied for specific types of structures [10]. for example, studied the effect of loading protocol on the cyclic response of wood frame shear walls. The authors observed that the number of cycles for each loading amplitude was the most sensitive parameter in measuring ultimate strength and deformation capacity. This first part of the paper reviews and compare existing cyclic loading protocols for testing various types of components and sub-assemblies and developed according to scientific methods, including two specifically developed for testing of non-structural elements. These two non-structural cyclic loading protocols are then used for testing two different common components of piping restraint installations (a Hilti MQS-AB-10 base hinge and a Hilti MQS-H10 connector). Characteristic response parameters resulting from each loading protocol are extracted and compared. Observations and recommendations are provided on the effects of using different loading protocols for the seismic qualification testing of suspended piping restraint installations.

2. Review of quasi-static cyclic loading protocols

Several scientifically based quasi-static cyclic loading protocols have been proposed over the years for the cyclic testing of structural and non-structural elements and systems. In the context of this paper "scientifically based" relates to the development of a loading protocol based on the statistical analyses of inelastic excursions obtained from time-history dynamic response analyses of singled-degree-of-freedom (SDOF) systems subjected to ground motions using the rain flow cycle counting method [2]. Since suspended piping restrain installations are typically made of steel components, this section concentrates on reviewing formal cyclic loading protocols that have been proposed for the testing of steel elements and systems. Two other cyclic loading protocols that have been developed from a scientific basis and widely used to test light-frame wood components and sub-assemblies are also reviewed. Finally, two recent cyclic loading protocols developed specifically for the testing of non-structural elements are reviewed and compared to the structural cyclic loading protocols. Note that before the development of these recent non-structural cyclic loading protocols, cyclic loading protocols developed for testing steel and wood structures were also used to test non-structural elements.

2.1. Cyclic loading protocols for testing steel structures

Two cyclic loading protocols have been developed and used extensively for the cyclic testing of structural steel components and systems: the ATC-24 protocol and the SAC protocol. These two cyclic loading protocols are reviewed in this section.

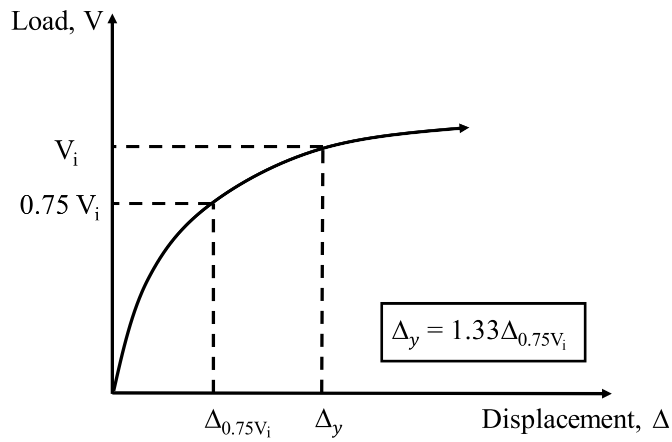

Fig. 1. Determination of first yield displacement, δ_y, of ATC-24 cyclic loading protocol.

2.1.1. The ATC-24 cyclic loading protocol

As part of the ATC-24 project, Krawinkler developed a loading protocol for the cyclic testing of components of steel structures [3]. The ATC-24 protocol is based on a yield deformation (Δ_y) obtained by extrapolating the deformation of the test specimen at 75% of its theoretical strength (V_i) measured either during the third cycle of the loading sequence, as illustrated in Fig. 1, or during a preliminary monotonic test. The cyclic loading history of the ATC-24 protocol shown in Fig. 2 was developed based on statistical studies of nonlinear time-history dynamic response of bilinear and stiffness degrading SDOF systems subjected to a set of 15 Western United States earthquake ground motions [11,17]. These studies provided statistical information on seismic demand parameters for inelastic systems having ductility capacities between 2.0 and 8.0. The parameters that were analyzed in order to provide support to the development of the ATC-24 protocol were the number of inelastic excursions, the individual plastic deformation ranges and the cumulative plastic deformation ranges. Table 1 presents the sequence of loading of the ATC-24 protocol. The first six cycles are force-controlled while the rest of the loading sequence is conducted in displacement-controlled mode.

2.1.2. The standard SAC cyclic loading protocol

Krawinkler [19] developed for the SAC (**S**tructural Engineering Association of California/**A**pplied Technology Council/**C**alifornia Universities for Research in Earthquake Engineering) Joint Venture steel research project in the United States two loading protocols for the cyclic testing of steel moment-resisting connections: a standard loading protocol and a near-fault loading protocol. Near-fault effects are not

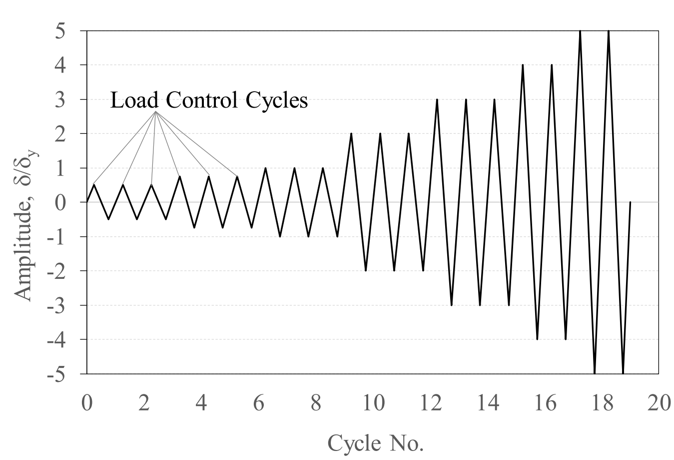

Fig. 2. ATC-24 cyclic loading protocol.