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Experimental study of slip-friction connectors for controlling the maximum seismic demand on a liquid storage tank

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ABSTRACT

Previous investigations have demonstrated that strong earthquakes can cause severe damage or collapse of storage tanks. Theoretical studies by other researchers have shown that using energy-dissipating anchors can reduce the axial compressive stresses in the tank shell compared to the fully anchored case. Those studies have also shown that using energy-dissipating anchors can reduce the displacement of the tank compared to the unanchored case. However, there is no experimental work to validate the results obtained from these numerical studies. This paper reports on a series of experiments using a shake table on a scale model PVC tank containing water. A comparison of the seismic behaviour of a fully fixed base system (tank with anchorage), a system free to uplift (tank without anchorage) and a partially fixed system (tank with slip-friction connectors) is presented. The slip-friction connectors are calibrated by performing cyclic tests. The experiments were performed using recorded ground motion scaled to the New Zealand design spectra for two Wellington sites. Measurements were made of the axial compressive stresses in the tank shell and the horizontal displacement of the top of the tank. The experiments showed the beneficial effects of using slip-friction connectors in storage tanks, reducing the uplift displacement in comparison with an unanchored tank and reducing the axial stresses compared to a fully fixed tank. A numerical model is proposed which corroborates these results.

1. Introduction

Storage tanks are essential structures that provide basic supplies such as water and fuel. Hence, these structures should remain operational after strong ground motions. Because of the importance of these structures, several studies have been carried out [1–3], and standards and design guides have been established [4–6]. Most storage tanks are anchored to their foundations due to the established belief that separation of the tank from the foundation is harmful, creating significant loading on the restraining mechanism [4,5,7]. However, numerical studies [8] have demonstrated that allowing uplift (separation) of the base plate from the foundation reduces the base shear and the overturning moment acting on the tank. On the other hand, unanchored tanks will likely experience larger displacements than those that are fixed to the foundation, damaging the piping that is connected to the tank [9–11]. An intermediate solution that reduces the seismic load in comparison with anchored tanks and reduces the displacements compared to those of unanchored tanks, are tanks provided with energy-dissipating anchors. Malhotra [12] reported using a numerical analysis the advantages of these anchors.

Firstly, the use of energy dissipating anchors lengthened the natural period and increased the damping of the tank system. Both effects produce a reduction of the seismic forces applied to the tank in comparison with a tank provided with conventional anchors. In comparison with a tank without anchorage, energy dissipating anchors reduced the horizontal displacements of the tank during an earthquake. The energy dissipating device proposed by Malhotra [12] is a torsional-beam steel damper. It dissipates energy through inelastic twisting of a mild-steel bar that is induced by the vertical movement of the tank wall. To the authors' knowledge, torsional beam dampers have not been implemented in storage tanks but have been used in buildings and bridges [13] and have shown to be effective in reducing the seismic demand. However, incursions in the plastic range cause permanent deformation of the mild-steel bar. Therefore, these connectors may require replacement after large earthquakes. Curadelli [14] proposed a device for energy dissipation for a spherical vessel that uses the deformation of lead. The device consists of two coaxial steel cylinders with lead rings between them. It dissipates energy through plastic deformation of the lead caused by relative displacement

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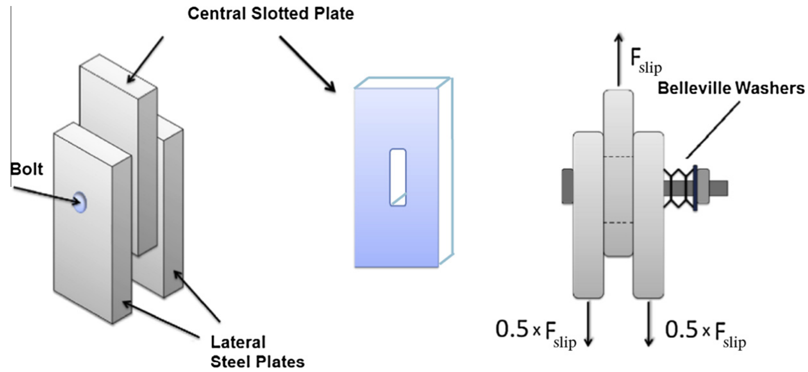

Fig. 1. Symmetric slip-friction connector.

between the cylinders [15]. As with torsional beam dampers, many incursions in the plastic range may cause permanent damage to the device leading to the replacement of the connector. This kind of connector is defined as a passive control system device [16,17] because it uses the motion of the structure to develop the control forces, i.e., it does not need an external source of power to work. A device that needs a large power source (different from the structure motion) to develop the control forces is called active control system device [16,17].

Another kind of fully passive control system to control the seismic forces acting on storage tanks is base isolation. Malhotra [18] proposed to base isolate a storage tank by removing the structural connection of tank wall and base plate. In that study [18], the tank wall is supported by flexible bearings and the base plate by the ground. Malhotra [18] reports that base isolation reduces dramatically overturning moment, base shear and axial stresses on storage tanks without increasing significantly the vertical displacements. Panchal and Soni [19] present a complete review of the state of art of base isolation on storage tanks. While fully passive control systems, mainly base isolation, have been investigated in numerous studies [18–22], active and semi-active control systems (which combine featured of passive and active control systems [16,17]) have not been studied for storage tanks to these authors' best knowledge.

Another passive energy dissipating device is the slip-friction connector. This kind of connector was developed originally for steel framed structures and dissipates energy through friction between parallel steel plates (Fig. 1). Butterworth [23] used a symmetrical sliding joint to dissipate energy in concentrically braced steel frames. MacRae et al. [24] developed a sliding hinge moment connection. Loo et al. [25] proposed a new type of symmetric slip-friction connector that avoids the use of brass shims. This reduced the cost of this kind of connector. Slip-friction connectors have the advantage of being stable and keeping their mechanical properties after several cycles of load. Despite the fact that semi-active control systems have shown a great potential to reduce the seismic forces on structures combining the best characteristics of passive and active control systems [16,17], slip-friction connectors were chosen for this study. The main reason for investigating slip-friction connectors is that they are inexpensive, simple and have the potential for being very effective. This suggested to the authors that slip-friction connectors may have advantages over existing technologies. The authors believe that the outcomes of this study will provide an alternative solution to diminish the seismic demand on storage tanks.

This work had two main objectives. The first was to study the feasibility of using slip-friction connectors to anchor storage tanks to their foundation. This involved cyclic tests with an Instron machine to determine the mechanical properties of the connector. The second objective was to quantify the seismic response of storage tanks anchored with slip-friction connectors in terms of the axial stresses in the tank wall and uplift of the tank base. This involved a PVC model tank that was subjected to earthquake motion on a shake table. To the authors' knowledge an experimental investigation on the use of any energy dissipating anchors on storage tanks had not been reported in the literature. Successful development of methods to reduce the seismic demand on storage tanks will lead to more efficient tank designs.

2. Methodology

2.1. Symmetric slip-friction connector

Slip-friction connectors are either asymmetric or symmetric. Symmetric connectors display superior elasto-plastic behaviour [25]. They transfer the friction force from a central plate to two outer plates (Fig. 1). The connector force, F_{slip}, is equal the total friction force between the plates. This friction depends on the friction coefficient, μ, of the materials in contact and the normal force, T, applied by the bolt. The central plate has a slot that allows relative displacement between the plates.

2.2. Belleville washers

Loo et al. [25] used Belleville washers to achieve the tensile force required in the connector bolt. Belleville washer are extensively described in [26]. A brief summary is presented herein. This type of washer behaves as a spring and within a range of deflections, which is provided by the vendor, these washers behave elastically. Fig. 2 shows the force–deflection relationship obtained for two washers. The washers are type M8-L-1.3-PB, from Solon Manufacturing Co., USA.

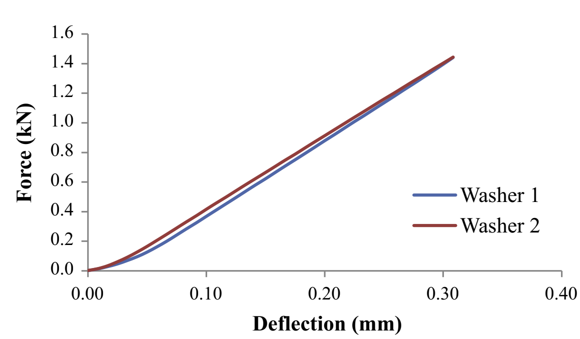

Fig. 2. Force–deflection relationship for Belleville washers, type M8-L-1.3-PB.