Seismic Isolation of Wine Barrel Stacks on Portable Steel Racks

C.B. Chadwell[1], K.R. Brennan[2], and M.W. Porter[3]

[1]Asst. Professor, Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA, USA
[2]Graduate Student Researcher, Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA, USA
[3]Graduate Student Researcher, Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA, USA

Email: chadwell@calpoly.edu, krbrenna@calpoly.edu, mwporter@calpoly.edu

ABSTRACT :

The International Building Code 2006 (IBC 2006) puts forth provisions that apply directly to steel storage racks in occupied structures. By following these provisions, it is shown in this paper that the current typical stacking method of 55 Gallon Bordeaux wine barrels on portable steel racks is not code compliant. Furthermore, collapsing wine barrels stacks during seismic events may not only result in monetary loss, but may also pose a hazard to employees and patrons in the barrel housing facilities. This, in fact, was evident in both recent research and recent earthquakes that have shown this common stacking practice to be at high risk of stack collapse during code design level earthquakes. Previous published research on the behavior of stacked wine barrels during seismic excitation (Marrow, 2002; Chadwell et al., 2006; Brown, 2007) has predominately focused on identifying the hazard, as well as characterizing the nonlinear rocking behavior of wine barrel stacks. The research presented herein describes an on going research program to provide wine barrel stack collapse mitigation by using seismic isolation bearings. The bearings are made of hardened steel ball bearings rolling inside a cubic polynomial surface fit from simulation to best minimize the force transmission between ground shaking and the wine barrel stack. What is unique to this particular application in seismic isolation is that unlike typical isolation, where a balance between maximum displacements and force transmission is sought, isolation of wine barrel stacks focuses only on collapse prevention. Excessive lateral displacements are not a main concern. This paper describes the need for an isolation bearing in the context of code design, the development and details of the bearing used, and test data collected from barrels stacked one and two levels high. Physical simulations conducted as part of this study demonstrate that the isolation bearing proposed can be a viable solution to the seismic hazard mitigation of wine barrel stack collapse. Furthermore, and perhaps more importantly, the application of this research may have broader implications for the collapse protection of stacked rigid bodies in general.

KEYWORDS: Seismic Isolation, Wine Barrel, Rigid Body Stacking

1. Introduction

California is one of the world's leading wine producers. In 2007, 554 million gallons of wine were shipped to U.S. and global markets. The economic value of the California Wine Industry is $51.8 billion and it creates 309,000 jobs within the state (Wine Institute, 2008). Wine production and the number of bonded wineries have increased steadily in recent years, making the industry an important part of California tourism and economy.

The viticulture industry stacks large volumes of wine barrel inventory on portable steel racks. Individual wine barrel stacks consist of two barrels at each level placed side by side on the rack below. These stacks range from one to eight levels high and typically, are not vertically connected by anything more than gravity, nor laterally connected by anything more than friction. Figure 1.1 shows a three level high barrel stack.

Figure 1.1 Traditional Wine Barrel Stacks (Morrow, 2002)

The majority of the wineries in California are classified as Seismic Design Category D with the majority located within 20 miles of an active fault (Marrow, 2002). Most recently, the vulnerability of wine barrel stacks was demonstrated during the San Simeon Earthquake (2003) that occurred near the Central Coast of California. Close to 20 wineries in this region experienced wine barrel stack collapse (Brown, 2007).

The ongoing research program started with the identification of the problem associated with typical wine barrel stacking methodology. Tests were performed on wine barrels stacks up to five levels in height (the limit of the testing facility) and, in most cases, partial to full collapse of the wine barrel stacks was observed. Analytical simulation models suggested that reducing the sliding friction at the bottom rack/concrete floor interface while maintaining the friction coefficient between the barrels above would result in a safer wine barrel stack. To accomplish this task, a seismic isolation bearing was designed and prototyped specific to the requirements of wine barrel safety. The isolation bearing consists of a high strength steel ball bearing contained by a woven Teflon covered steel cubic polynomial surface. The research presented herein describes the need for an isolation bearing in the context of code design, the development and details of the bearing used in testing, and test data collected from one and two level barrel stacks.

2. Previous Research

Research by Chadwell et al., 2006, involved a one level barrel stack. Tests using pulse wave frequencies of 2Hz to 8Hz were used to identify the frequencies causing rocking and sliding. A single barrel analytical model was constructed to investigate the nonlinear behavior of barrel rocking and sliding. System friction and damping values were fit to match the barrel response recorded from testing. The model was then used to predict barrel response due to three specific ground motions. The ground motion records used were originally chosen for their individual characteristics. The records selected are classified as earthquakes that have a 10% probability of exceedance over a 50 year period (SAC, 1996). The records used are the LA16 (Rinaldi Receiving Station, Northridge, 1994), LA18 (Sylmar, Northridge, 1994), and LA19 (North Palm Springs, 1986). The ground motion records containing shorter period energy (LA18 and LA19) were selected to provoke sliding type behavior in the original stacking configuration, while the ground motion record containing longer period energy (LA16) was chosen to induce rocking in the stack. The analytical model provided fair correlation with data collected from the physical simulations.

Research by Brown, 2007, characterized the barrel stack response through full scale testing of multiple level stacks. Wine barrel stacks of two, four, and five levels were tested using the three representative ground motions. The majority of the tests of four and five level stacks, and some of the two level stacks, resulted in partial to full stack collapse. Subsequent analyses of the data classified the main collapse mechanisms as either sliding, rocking, or a combination of sliding and rocking. It was determined that stack collapse greatly depended on stack slenderness and the friction at each barrel/rack interface. High frequency motion was shown to cause “walking” of the top barrels off their support racks in stacks four levels and higher. Research by Brown concluded with a preliminary investigation of stack response using ball bearings housed in a Teflon socket mounted directly to the base of the bottom rack in the wine barrel stack. As consistent with the theory of seismic isolation, it was shown that isolating the stack in this fashion, and allowing it to slide as a single unit relative to the ground, is an effective method of collapse mitigation**.**

3. Wine Barrel Stack Configuration Subject to IBC 2006 Lateral Design Forces

From past earthquake observation, it is abundantly evident that the current typical wine barrel stacking system is completely inadequate. Thus, it is of interest to investigate whether this current wine barrel stacking system is compliant with IBC 2006 code provisions. ASCE 7-05, Section 15.5.3 (ASCE, 2005) puts forth provisions for the design of steel storage racks. To investigate, a demand/capacity analysis was conducted and is provided herein. The seismic demands were obtained from the USGS (Ground Motion Parameter Calculator, Leyendecker, et al.) for the Paso Robles, California wine region 24 miles from the epicenter of the 2003 San Simeon Earthquake. The design base shear for the typical four level barrel stack is calculated as 1.49 kips. The corresponding base shear distribution, shear demand, and moment demand are found at the bottom of each barrel level. The demands at each barrel level are compared against the capacity at each barrel level as dictated by either a sliding failure between the rack and the barrel, or a rocking (or overturning) type failure at the rack/barrel interface. The sliding failure is calculated from the normal force at each barrel level times the steel to steel coefficient of static friction (0.3) for the steel barrel bands to rack contact and the steel to concrete coefficient of friction (0.45) for the steel bottom rack to concrete contact (Beardmore, 2006). Overturning capacity is calculated at the point when the lateral load demand exceeds the stabilizing downward force of gravity (Figure 3.1).

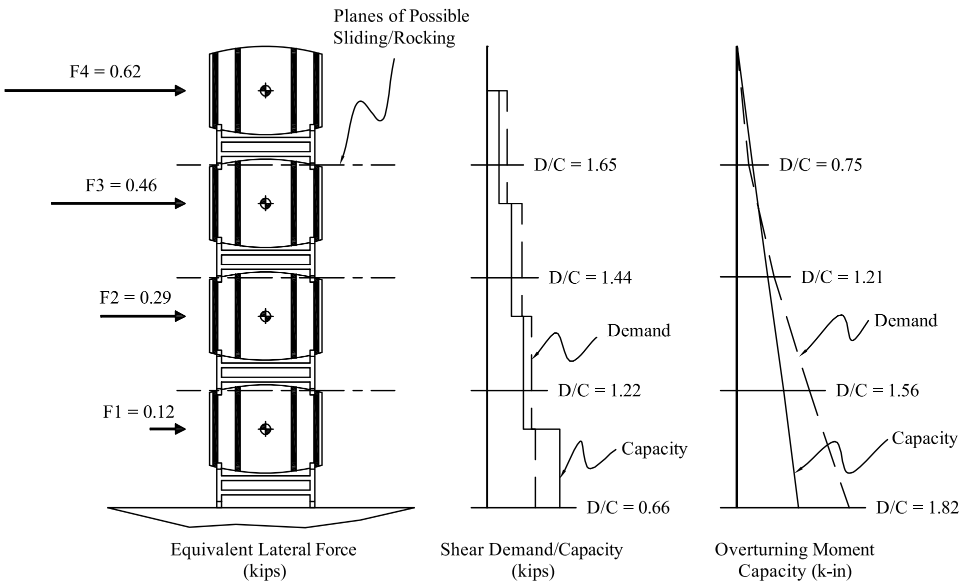

Figure 3.1 Existing Configuration Demand/Capacity

Analysis suggests that the stack in the current configuration cannot withstand the code required minimum forces using the equivalent static lateral load procedure. Shear demands exceed capacities at barrel levels two, three, and four indicating a sliding type failure. The moment demands exceed capacity at barrel levels one, two, and three associated with the code forces indicating potential rocking. Both the sliding and rocking mechanisms contribute to potential stack collapse. This finding is consistent with the observations during the San Simeon Earthquake reconnaissance (Chadwell, 2006).

4. Isolation System Development

The proposed base isolation system allows for unrestrained lateral displacement of the entire barrel stack relative to the concrete floor. By reducing the friction coefficient at the base of the system, the effective base shear capacity and associated force transmission to the barrel stack are proportionately reduced. The sliding demand/capacity ratio of the bottom barrel level, at the location of the isolation bearings, becomes the controlling failure mechanism. Sliding at this location allows the barrel stack to move as a single unit. Analysis shows that a friction coefficient of approximately 16% and below would provide seismic barrel stack protection for a four level barrel stack.

The isolation device prototyped for collapse mitigation is a steel ball bearing that rolls inside a polynomial curved surface milled from steel. The test results presented here are for the steel on steel bearing. The authors are currently preparing to test an identical bearing that is Teflon coated steel on steel. The best fit curved surface profile was fit through computer simulation to minimize the force transfer at the base rack atop the typical warehouse concrete floor. In design of the bearing, the idea was to minimize the transference of forces from high frequency earthquake vibration by minimizing the initial bearing stiffness anywhere between near zero to zero. This was achieved by an initial flat plate section of the bearing. Secondly, for near source type ground motions containing either fling step or velocity pulse type characteristics, the design was such that the ball bearing force transmittance was limited. This was achieved when the ball bearing, rolling upon a curved surface, reaches the critical friction angle where the ball slides against the Teflon while continuing to roll upon the concrete warehouse floor.

In early prototyping, decisions about the number and size of the ball bearing to use were considered (Brown, 2007). It was found that 16 contact points of 0.75 in diameter ball bearings was sufficient to minimize potential damage to the warehouse concrete floor during service for a five level barrel stack. A five level barrel stack weighs approximately 6,500 lbs resulting in an estimated load at each point of contact of 400 lbs. As the ball bearings are hardened steel, they leave a small pock mark in the floor slab at the point of contact and introduce a force that has to be overcome before the stack can begin to move.

The behavior of the bearing (Figure 4.1) is such that as the ground moves underneath the device due to seismic excitation, the ball is forced to roll against the cubic surface similar to the well established friction pendulum system. However, because the surface is cubic, the resulting force displacement is roughly parabolic and the tangent stiffness consequently changes linearly with increasing lateral displacements.

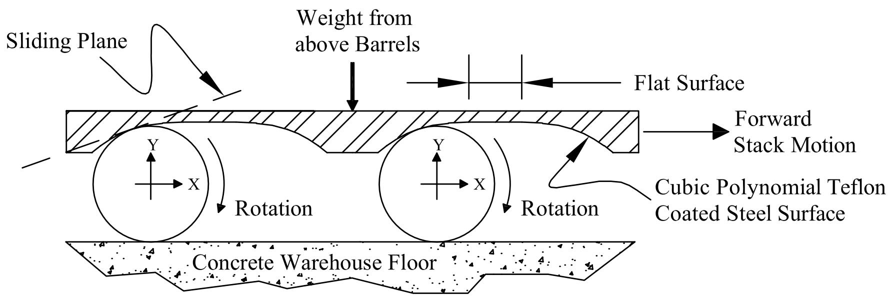

Figure 4.1 Isolation Device Schematic

As the hardened steel ball bearing rolls up the curve, the force tangent to the Teflon/ball bearing surface reaches a capacity that is dictated by the friction coefficient between Teflon and steel. Once this capacity is reached, the ball slides against the Teflon surface, essentially creating an equivalent yield force (force transmission fuse). While at this yield point, the bearing will no longer travel along the cubic surface but will continue to travel on the ground below, increasing displacement, while transmitting a finite force up through the stack equal to the friction coefficient times the weight above. Unique to this type of system is that the horizontal yield force is exactly the same as the friction force tangent to the contact of the bearing with the Teflon surface. Furthermore, the reaction at the concrete ball bearing contact point is equal to the normal force at the Teflon/ball bearing contact point. This can be shown using static moment equilibrium at the center of the ball bearing in the deformed configuration (Figure 4.2).

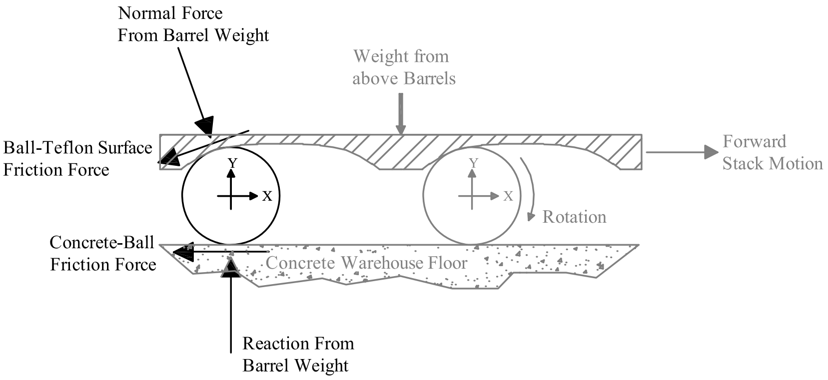

Figure 4.2 Free body Diagram of Ball Bearing

Due to the lower friction coefficient between the ball bearing and the upper curved surface compared to the ball bearing contact point with the concrete surface, sliding will always occur at the Teflon/steel contact point. Figure 4.3 shows the force displacement articulation model for the wine barrel rack mounted on the prototype seismic isolation bearing. The force displacement curve shown has a yield force of 0.125 kips consistent with a two level stack and an assumed Teflon/steel friction coefficient of 5%. Details of the theoretical development of the force displacement articulation model are not provided here for brevity.

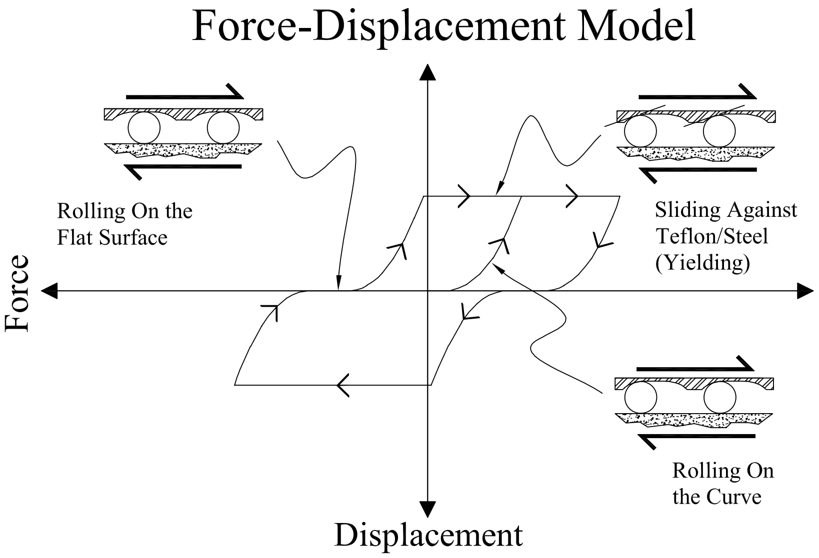

Figure 4.3 Force-Displacement Articulation model of the Isolation Device

When the ball reaches the yielding plateau, increased displacements are seen with no increase in force. Essentially, the tangent stiffness of the system drops to zero. Also, in Figure 4.3, a flat region (a region of zero slope) can be observed near the origin. This flat surface is a direct correlation to a physical flat surface on the device itself. It is meant to restrict transmission of forces from high frequency, high acceleration type ground motion. In previous tests of non-isolated stacks, high frequency motion was shown to cause a "walking" effect of the top barrels in stacks four levels and higher (Brown, 2007). On the flat surface, the tangent stiffness drops to zero as pure rolling occurs and the rack is free to oscillate back and forth without any transmission of force through the stack.

5. Experimental Setup

Full scale shake table testing to determine preliminary performance of the seismically isolated wine barrel stacks, as compared to previous studies (Chadwell et. al, 2006 and Brown, 2007), was conducted in the Parsons Geotechnical/Earthquake Engineering Lab on the campus of California Polytechnic State University, San Luis Obispo, California. Tests utilized typically configured Topco WR2 type wine barrel racks capable of holding two 55 gallon French Bordeaux wine barrels each, representing the industry standard for this application. Following current industry stacking methods, tests were conducted on both one level and two level stacked barrel configurations. A concrete slab was designed to mimic conditions at local wineries and mounted directly to the shake table. The isolation device was attached to the base barrel rack and placed directly onto the slab. Subsequent barrel levels were added to achieve the desired testing height. An instrument frame was used in order to restrain barrels from excessive displacements, as well as provide mount for data acquisition devices. (Chadwell et al., 2006)

Data was collected using displacement transducers located at various locations relative to the wine barrel center. A horizontal transducer was mounted to the instrument frame and connected to the back of every barrel. Two angled transducers, one mounted to the front of the shake table and the other to the instrument frame, were used to measure vertical movement of the barrel. Accelerometers were also mounted at the center of mass of one side of the barrel level. Figure 5.1 depicts the schematic for instrumentation and experimental setup of the one level barrel stack. Instrument setup for the two level barrel stack has a similar configuration.

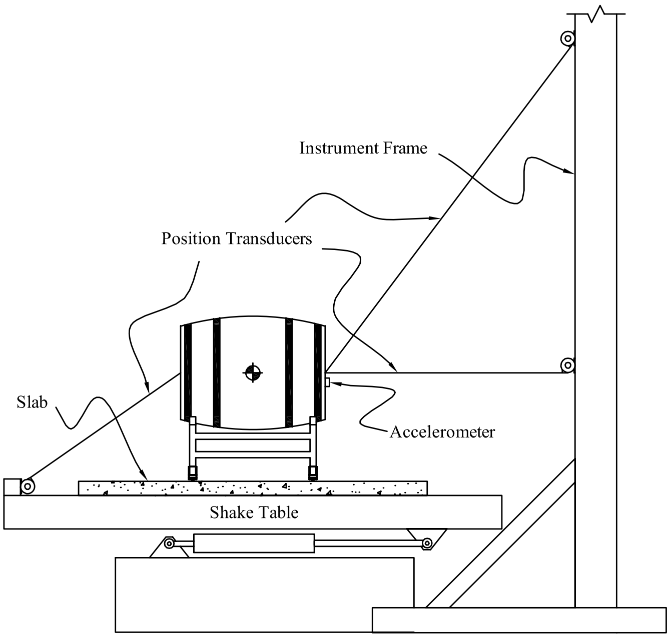

Figure 5.1 Experimental Setup

6. Full Scale Test Results

Consistent with previous research, three earthquake ground motions were used to evaluate the performance of the isolation device (LA16, LA18, and LA19). At the time of authorship of this document, testing of the one and two level barrel stacks with the steel on steel seismic isolation bearing has been conducted. Displacement time histories of the base barrel are provided for the one and two level barrel stacks in Figure 6.1. In all tests conducted, neither sliding of the barrel upon rack nor barrel rocking was observed. In fact, the total relative displacements were concentrated between the base rack and the simulated concrete warehouse floor.

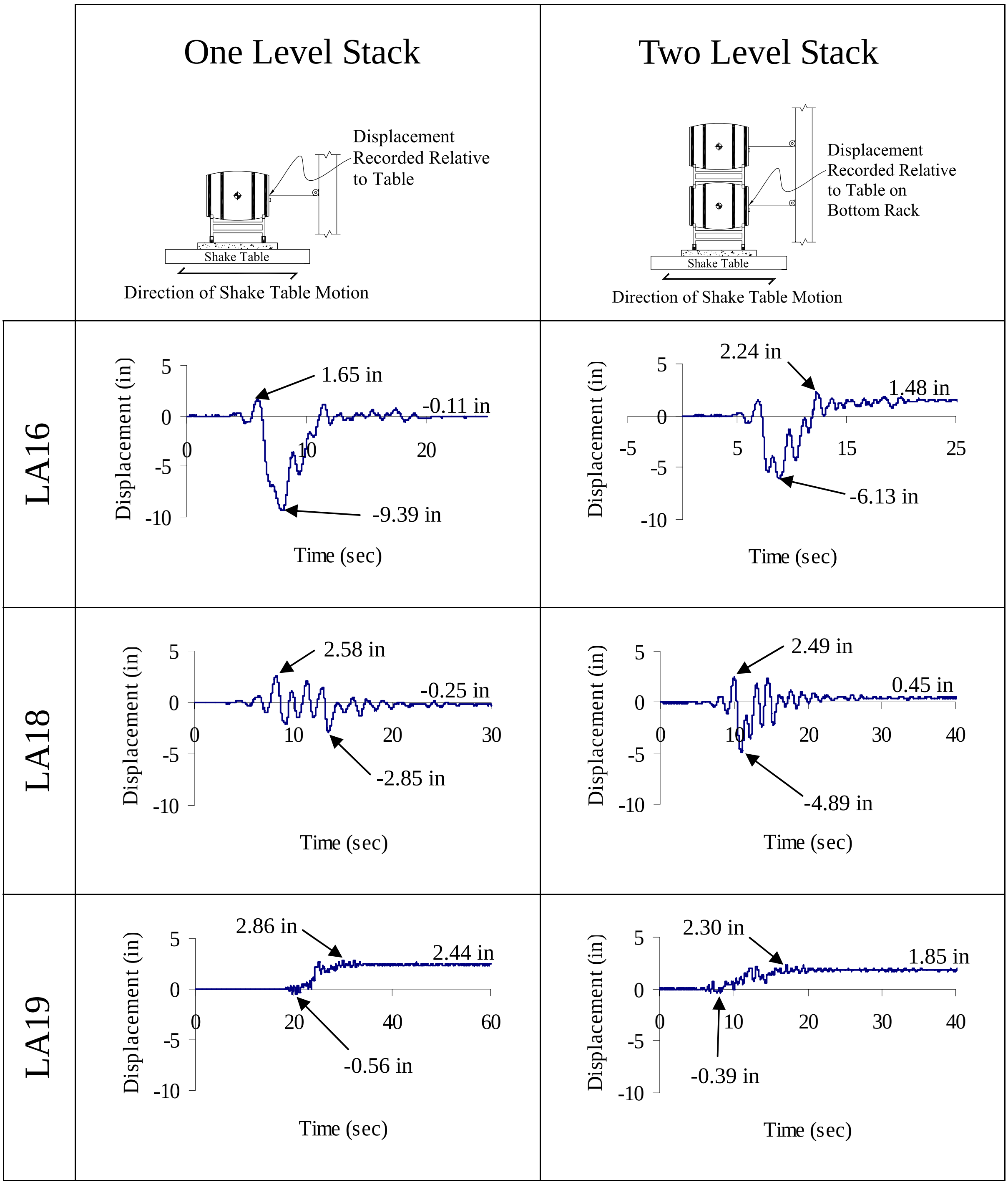

Figure 6.1 Stack Displacement Time Histories for LA16, LA18, LA19

7. Conclusions and Future Research

Evaluation of the current practice of wine barrel stacking using the IBC 2006 demonstrates that this stacking method is currently not code compliant. Recent earthquakes near regions with high concentrations of wineries demonstrate that the current system of stacking is subject to collapse during moderate to strong ground shaking. Previous research has shown through experimental testing that typical California design level earthquakes will more than likely collapse a wine barrel stack of four and five barrel levels high, and in some cases, will collapse even a stack of two barrel levels high. Experimental evidence from initial full scale testing of wine barrel stacks mounted upon an isolation system consisting of a steel ball bearing rolling/sliding in a concaved cubic polynomial surface is promising. The device was shown to function as designed for the wine barrel configurations tested and to mitigate wine barrel stack collapse by effectively decoupling the wine barrel stack from the ground motion. Furthermore, as the Teflon/steel coefficient of friction is smaller than the steel on steel coefficient of friction, it is anticipated that the seismic isolation bearing will provide adequate stack performance up to and including the five level barrel stack during the next phase of testing. Research is currently underway to exactly characterize the force displacement articulation model for the bearing to match the recorded test data. With a functioning analytical simulation model, this research program will conclude with a statistical analysis to establish the probability of failure of wine barrel stacks as both a function of stack height, as well as stacks with and without the isolation bearings.

References

American Society of Civil Engineers (2005) Minimum Design Loads for Buildings and Other Structures: ASCE 7-05

Beardmore, R (2006), Friction Factors; http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm

Brown, D.T. (2007), *Seismic Response of Wine Barrel Stacks* Graduate Research Thesis, California Polytechnic State University, San Luis Obispo

Chadwell, C.B., Stanley, J.M., Marrow, J.M. (2006), *Nonlinear Analytical Modeling and System Verification of a Wine Barrel on a Portable Steel Rack Subject to Seismic Excitation*, 2006 8th National Conference of Earthquake Engineering, San Francisco, California

Marrow, J.M., (2002) *The Seismic Vulnerability of the California Wine Industry – An Experimental Assessment*, 2002 Structural Engineer’s Association of California Annual Convention, Santa Barbara, California

Sac Joint Venture Steel Project Phase 2 (1997), *Develop Suites of Time Histories: Project Task 5.4.1*, Draft Report, SAC

USGS (2008), Ground Motion Parameter Calculator; www.usgs.gov

Wine Institute (2008), California Wine Industry Statistical Highlights; www.wineinstitute.org