Experimental Investigation of the Seismic Performance of Substation Porcelain Insulator Posts in High Voltage Disconnect Switches

K.M. Mosalam, M.A. Moustafa, M.S. Günay, S. Takhirov
University of California, Berkeley

15 WCEE
LISBOA 2012

SUMMARY
The study presented in this paper aimed at carrying out experimental research of the porcelain insulator posts of electrical disconnect switches. The experiments consisted of static and dynamic shaking table testing. The static and resonance-search tests aimed at obtaining basic characteristics of the insulator such as lateral stiffness, failure load and displacement and fundamental frequency. The main part of the study was concerned with dynamic tests of a part of the switch and compare the results with the as-installed disconnect switch test results to demonstrate and validate the concept of substructuring. Substructured 550-kV switches were tested first to study the effect of rotations of the top of the switch support structure on the seismic behaviour and performance of the switch. The second substructured test focused on 230-kV switches as a first step towards developing a real time hybrid simulation technique for testing disconnect switches.

Keywords: Electrical disconnect switches, hybrid simulation, porcelain insulator, shaking table tests.

1. INTRODUCTION

Disconnect switches are a key component of power transmission and distribution systems. They are used to control the flow of electricity between all types of substation equipment and used to isolate this equipment for maintenance. The disconnect switches are normally mounted on support structures and can be opened or closed using metallic tubes called main blades that connect the insulators poles together from the top. This study is focused on vertical-break switches where the main blade is opened vertically in the phase plane. Two types of switches were considered: 230-kV and 550-kV switches. Typical field installations of the switches considered in the study are shown in Fig. 1.1.

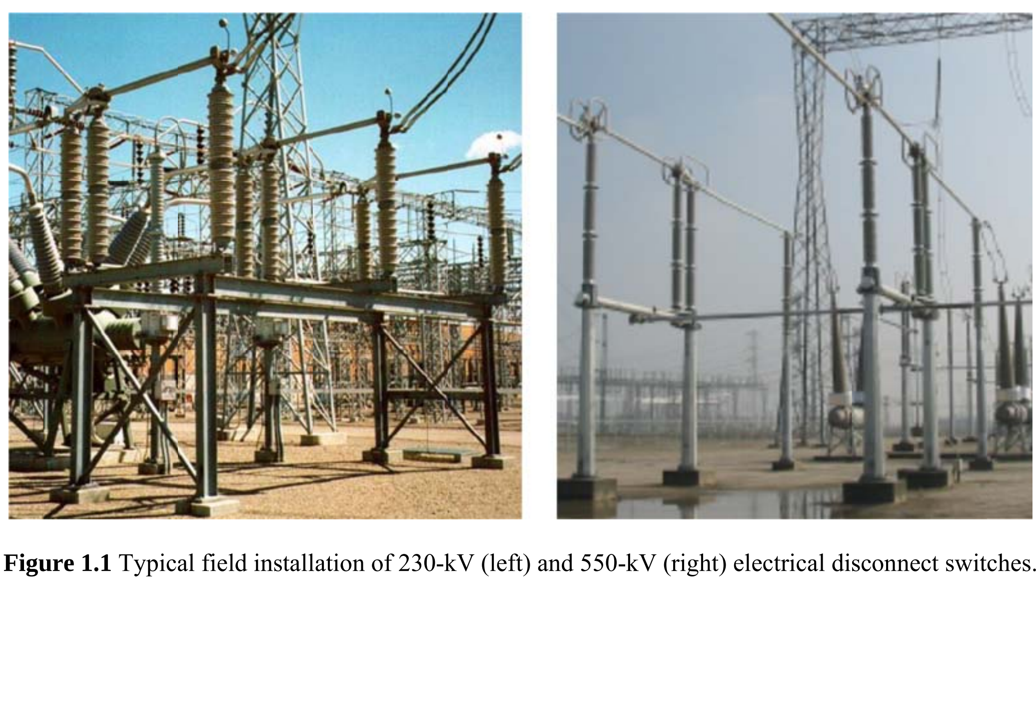


Figure 1.1 Typical field installation of 230-kV (left) and 550-kV (right) electrical disconnect switches.

Due to the severe damage that the switches and porcelain insulators have experienced during many earthquakes (Fujisaki, 2009), and to mitigate the vulnerability of new disconnect switches and other electrical substation equipment in Northern America, the Institute for Electrical and Electronics Engineers (IEEE) is developing and updating guidelines for seismic testing and qualification of disconnect switches. These guidelines require certain disconnect switches to be tested on shaking tables using an IEEE693 (IEEE, 2005) spectrum-compatible strong motion to qualify the switch at certain performance levels. If the disconnect switch does not qualify according to the IEEE guidelines, modifications of the switch or its support structure should be performed. The switch should then be re-tested and pass in order to be qualified.

This process, of repeating the shaking table test for the disconnect switch after design modifications is time-consuming, expensive, and sometimes not practical. This was the motivation for developing a new testing approach that can easily accommodate performing such design modifications, especially in the support structure. The proposed approach is based on the concept of real time hybrid simulations (RTHS) using a small shaking table for testing only a component of the disconnect switch, such as a single insulator, with an online computational model for the support structure. The main advantage of the hybrid simulation (HS) approach is its flexibility to evaluate any support structure as a numerical simulation model. In this approach, a simple modification in the computer model can help to minimize amplification of the support structure and frequency coupling between the switch and the support structure and as such can streamline process of research and development. Due to the complex nature of disconnect switches with the different components, fittings and mechanical parts, the suggested approach is not meant to substitute the full switch qualification tests. However, it could save expensive full-scale shaking table tests for every time a modification in the support structure or the switch is made. Moreover, the design of the support structure can be optimized using the suggested HS testing approach, which is the essence of the experimental testing program conducted in this study.

The ultimate goal of the experimental study was to develop the HS approach for vertical-break switches. However, only the first stage of the study, which focused on demonstrating the concept of substructuring to be utilized in RTHS, is presented in this paper, whereas the development and validation of the RTHS framework is discussed in (Günay et al., 2012). Two types of switches were considered for the study; namely 230-kV and 550-kV disconnect switches. The experimental program started with several frequency analyses and static cyclic-loading calibration and fragility tests in order to acquire basic knowledge of 230-kV and 550-kV single porcelain insulator posts.

Several substructured dynamic tests were carried out by testing part of the disconnect switch using offline signals that were generated from previous tests of complete switch assembly with the support structure (called as-installed switch in this study). The results of the substructure and as-installed switch tests were then compared. Two tests were conducted for this purpose. The substructure test with offline signals was conducted on the 550-kV switch (three-insulator posts assembly) on the six-degree-of-freedom shaking table of the Pacific Earthquake Engineering Research (PEER) Center without support structure. Moreover, the 550-kV substructured test aimed at evaluating the contribution of support structure rotations to the seismic performance of the disconnect switch. Out-of-plane rotations are expected to have significant values due to the flexible nature of the 550-kV support structure in the out-of-plane direction. The second test focused on testing a single porcelain insulator of a 230-kV vertical-break disconnect switch on a small unidirectional shaking table at the Structures Laboratory of UC-Berkeley. The effect of rotations was assumed to be insignificant in the 230-kV case due to the high stiffness of the braced frame support structure of this switch type. Thus, the main objective of that test was verification of the single insulator substructuring concept to be utilized in the intended RTHS framework on the same unidirectional shaking table.

2. STATIC AND RESONANCE SEARCH TESTS

The conducted static tests were the first stage of the multi-stage experimental study. Two different types of porcelain insulator posts were tested. The first type included one 230-kV insulator post which consisted of 2 sections and had an overall height of 80 in., while the second included several 550-kV insulator posts each consisting of 3 sections with an overall height of 151 in. A complete set of static tests comprised a ramp cyclic-loading test to determine the lateral stiffness of a single insulator post and a fragility test where the insulator was pulled until failure to determine its failure cantilever load, displacement at failure and ultimate strain. Besides the cyclic and fragility tests, impact hammer tests were conducted to determine the resonant frequency of the insulators.

2.1. Setup of Static Tests

For conducting the 230-kV insulator unidirectional cyclic-loading and pull tests, the two sections that form a single insulator post were assembled and attached to the reaction steel frame using a rigid base plate. The 550-kV insulators were tested in a similar setup by attaching them to the laboratory strong floor by means of a stiff adapter plate. Fig. 2.1 shows the static test setups used for both 230-kV and 550-kV insulator posts. A wide range of instruments was used to measure forces, displacements and strains. Moreover, for the impact hammer tests, accelerometers were used for frequency estimates.

In a typical disconnect switch, three insulator posts are used and designated as jaw, rotating and rigid posts. In 230-kV switches, all three posts were assembled from the same insulator type. However, in 550-kV switches, the rotating post had lower cantilever rating and stiffness than other two. Only rotating 550-kV posts were considered for fragility tests in this study.

Figure 2.1 Cyclic-loading and fragility test setups used for 230-kV (left) and 550-kV (right) insulator posts.

2.2. Impact Hammer (Resonance-search) Test

For this test, an impact was applied using a rubber hammer to the top of each of the 230-kV and 550-kV insulator posts to develop an impulse that excites all the vibration frequencies. The measured accelerations at top of the post were post-processed using the Fast Fourier Transform (FFT) to estimate the resonance frequencies. A typical plot showing FFT amplitudes of the accelerations recorded in one of 230-kV tests is shown in Fig. 2.2 along with the dominant resonant frequency. The resonant frequency for the 230-kV insulator was in the vicinity of 19 Hz while that of 550-kV insulators was found to be 16 Hz.

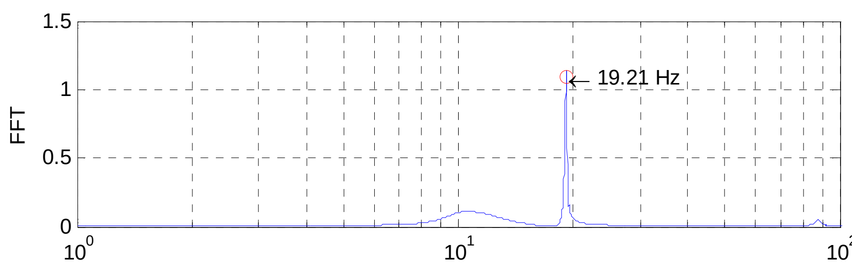


Figure 2.2 Typical FFT of impact hammer acceleration records for 230-kV insulator post.

2.3. Cyclic Loading and Fragility Tests

Several ramp displacement cycles of the same amplitude were applied to the top of the 230-kV and 550-kV insulator posts. The purpose of this test was to obtain the force-displacement relationship and determine the stiffness of the insulator. The average lateral stiffness of the tested 230-kV insulator was found to be 1.6 kip/in. On the other hand, the stiffness of the 550-kV rotating post was found to be 0.87 kip/in., which is less than 1.33 kip/in. stiffness estimated for jaw and rigid posts.

After cyclic tests, the top of the insulator was pulled until failure to investigate the damage propagation, mode of failure, and determine the failure values. Fig. 2.3 shows the force-displacement relationship until failure for both 230-kV and 550-kV insulator posts. The failure load, displacement and maximum strain values were found to be 2.2 kips, 1.60 in. and 1130 μstrain, respectively, for the 230-kV insulator and 3.1 kips, 3.60 in. and 2450 μstrain, respectively, for the 550-kV rotating insulator post. Both 230-kV and 550-kV porcelain insulator posts showed a brittle mode of failure. Fig. 2.4 illustrates the propagation of damage and brittle failure in the case of 230-kV insulator post.

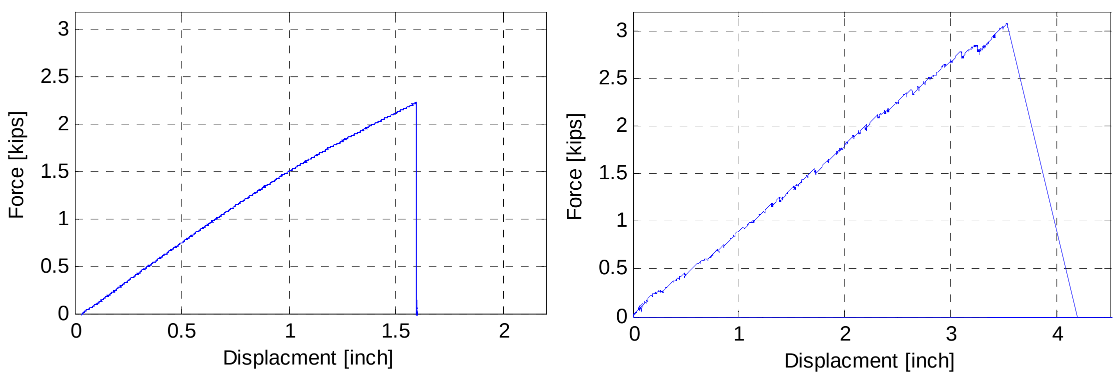


Figure 2.3 Force-displacement relationship until failure for 230-kV (left) and 550-kV (right) insulator posts.

Figure 2.4 Propagation of damage and failure mode of 230-kV porcelain insulator post in fragility test.

3. SUBSTRUCTURED DYNAMIC TESTS: 550-KV SWITCHES

Two different disconnect switches were considered for substructured dynamic testing. This section presents the tests of 550-kV vertical break disconnect switch typically installed on a support structure consisting of two steel columns. The main objective of this test was to evaluate and quantify the contribution of the support structure rotations to the straining actions of the switch and porcelain insulator posts. That was to investigate whether it is necessary to consider a rotational degree of freedom (DOF) if a HS test is to be conducted for the 550-kV switches.

3.1. Test Setup and Input Signals

The substructure tested in the 550-kV case comprises three insulator posts with all the switch blades and live parts without the switch supporting columns (support structure). Two offline signals were generated for the substructured test from accelerations and rotations measured on top of the support structure in the as-installed configuration test conducted on the PEER shaking table in 2010 (Takhirov, 2011). The first signal included a single out-of-plane translational component, while the second signal included both out-of-plane translational and rotational components. Only one rotation component is considered because the frame is rotationally flexible only in the out-of-plane direction and rotationally rigid in-plane. The test setup for the as-installed switch test and substructured test without support structure, showing a representation of used input signal in substructured test, are shown in Fig. 3.1.

Figure 3.1 Test setup for 550-kV as-installed switch test (left) and substructured switch without support structure (right) showing signals generated from the as-installed test and applied to the substructured test.

The as-installed switch tests were part of a seismic qualification test required by IEEE 693 (IEEE, 2005). For a switch to qualify, several shaking table tests are required with many configurations and at certain intensities. The same conditions of testing were replicated for the substructure tests without support structure. The different configurations of the switch are identified according to the state of the switch ground and main blades. Based on the state of these two blades, the switch can have the following main configurations: Open-Open (OO), Open-Closed (OC) and Closed-Open (CO).

Each of the three configurations was tested at a certain scale (intensity-level) twice using the single out-of-plane translational component (i.e. signal A, Fig. 3.1) and using the out-of-plane translational and rotational components (i.e. signal A+B, Fig. 3.1). Two scales were sought for testing, namely 25% and 50% scales. Different types of instrumentation which included several accelerometers, position transducers and strain gauges were used in these shaking table tests (Mosalam et al., 2012).

3.2. Effect of Rotations in Substructuring Tests

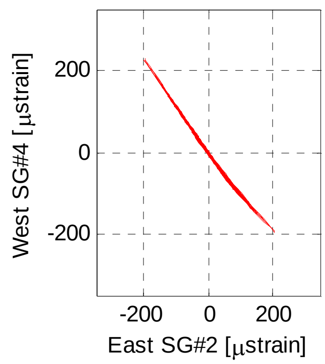
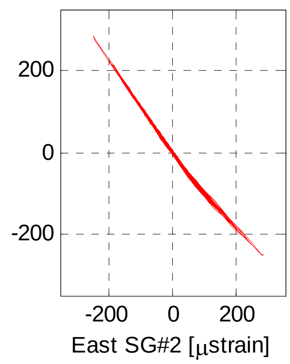
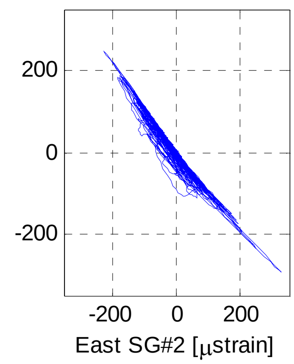
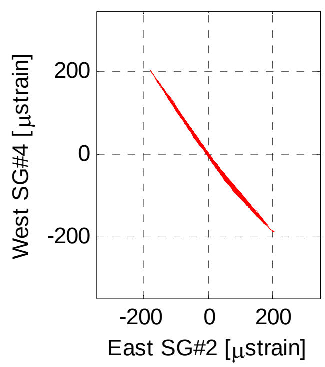
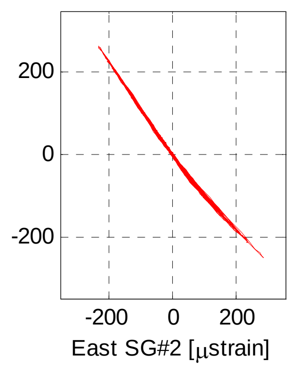
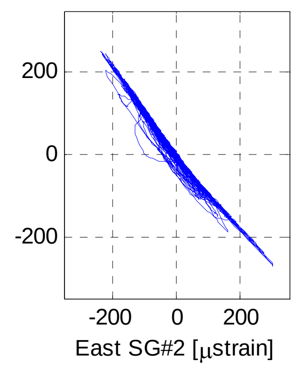
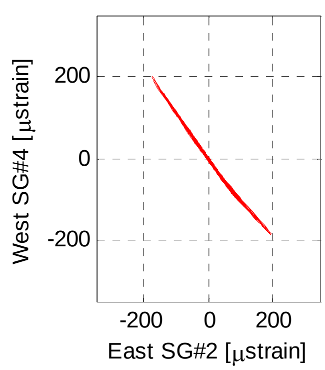
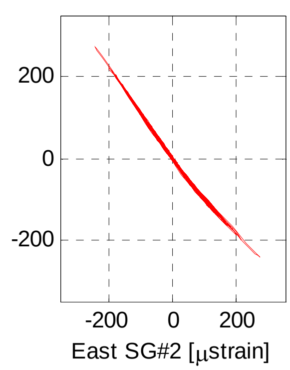
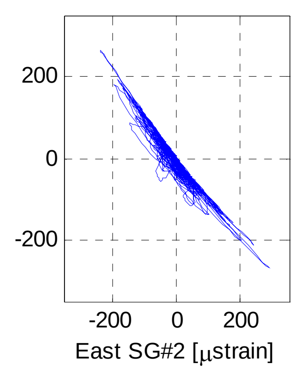
For the sake of evaluating the effect of rotations on switch performance, the tests driven by a single translational out-of-plane signal, and those driven by a combined translational and rotational signal were compared separately against the as-installed switch test for the three switch configurations, namely OO, OC and CO. Two response quantities were considered for such comparisons: the strain at the jaw-side insulator bottom and the relative displacement of the jaw-side insulator. The jaw-side insulator is not connected directly to another post, especially when the top blade is open.

3.2.1. Comparison of Strains

The measured strains at the bottom of the jaw-side insulator in two opposite sides (East and West according to insulator pole orientation on the PEER shaking table) are considered and designated as

SG#2 and SG#4, respectively. The jaw insulator strains in substructured and as-installed switch tests were compared for the three configurations as summarized in Table 3.1. The comparison showed how the rotational component of the signal led to better match with the as-installed switch results.

Table 3.1 Comparison of insulator strains in the substructured tests with those of the as-installed switch test.

	Substructured Test (without rotation signal)	Substructured Test (with rotation signal)	As-installed switch Test
Open – Open			
Closed – Open			
Open – Closed			

3.2.3. Comparison of Relative Displacements

The relative displacements of the jaw-side insulator were determined in the out-of-plane direction as the difference between the displacement measured at the top of the insulator and that measured at its base. The comparison of the jaw post relative displacements between the substructured test with and without the application of the rotational component and that from the as-installed switch triaxial test is shown in Fig. 3.2 for the OC configuration. Similar to the strains, inclusion of the rotational component of the input signal results in better match with the relative displacements from the as-installed switch test. Although not shown here due to limitations of the paper size, same conclusion was drawn from the other switch configurations. The good match in case of rotation inclusion verifies the validity of substructuring in 550-kV switches using a rotational DOF.

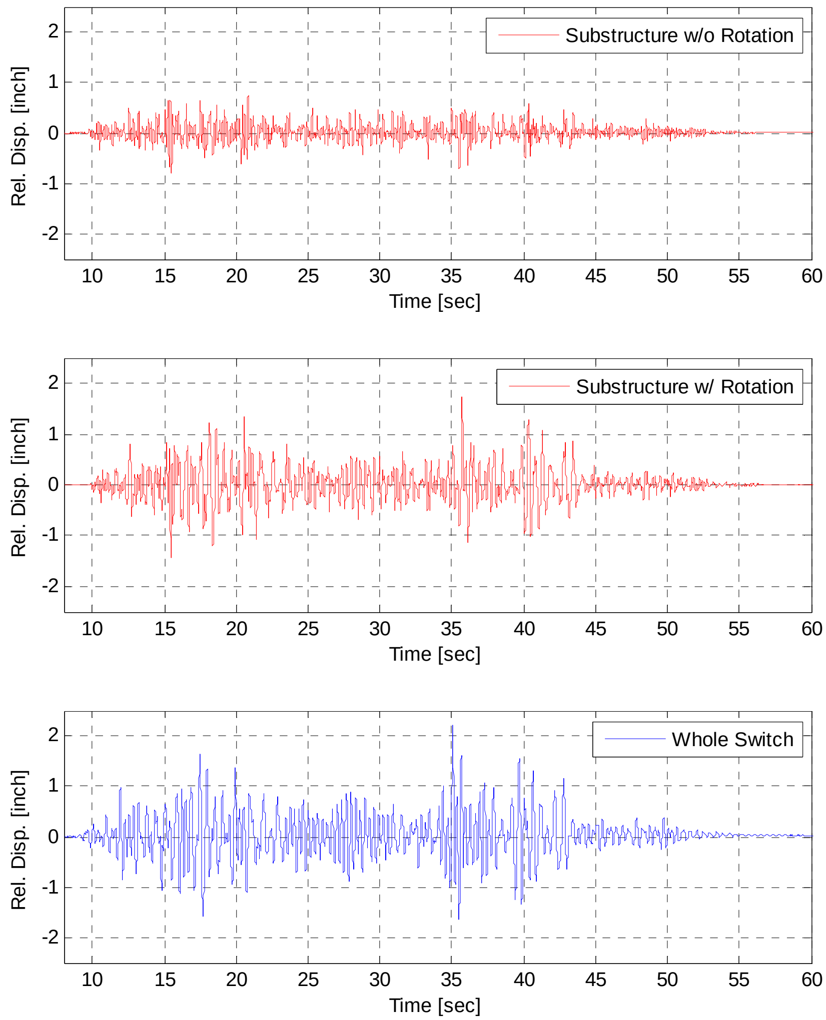


Figure 3.2 Relative displacement between the jaw post top and bottom for different tests in OC configuration.

4. SUBSTRUCTURED DYNAMIC TESTS: 230-KV SWITCHES

After evaluating the effect of support structure rotations and acceptable verification of the substructuring concept in the 550-kV switches, response of 230-kV switches that comprise braced support structure was investigated. Due to the rigid nature of the 230-kV switch support structure, the rotations are not expected to contribute significantly to the response of the insulator posts. Accordingly, the 230-kV switch is more suitable for developing the intended unidirectional RTHS testing with a single translational signal applied. Thus, the substructuring in 230-kV switches focused on testing a simple idealized substructure: a single insulator post with relevant live parts. After the substructuring concept was properly verified, the single insulator post was used as the physical specimen in all of the conducted HS implementation and validation tests (Mosalam et al., 2012).

4.1. Test Setup

The single substructured 230-kV insulator post was tested on the uniaxial shaking table at the Structures Laboratory of UC-Berkeley. Similar to the 550-kV switch substructured tests, the 230-kV insulator test was driven by an offline signal that was generated from the acceleration record on top of support structure in the as-installed 230-kV switch tested on PEER shaking table in 2008 (Takhirov, 2008). In the 230-kV case, only the OO configuration was considered when jaw post is disconnected on top from other two posts, allowing it to be used independently as a substructure. The as-installed switch on PEER shaking table and substructured insulator post on uniaxial shaking table are shown in Fig. 4.1. The connection at the insulator base and live parts at top are also shown in the same figure. Different types of instrumentation were used including strain gauges, wire potentiometers, accelerometers, and a vertical displacement transducer to measure the uplift (if any) of the unidirectional shaking table.

Figure 4.1 As-installed 230-kV disconnect switch mounted on the PEER shaking table during a seismic qualification test in 2008 (left), substructured single insulator post setup (middle) and close-up views of single insulator base connection and top live parts (right).

The unidirectional shaking table performance and capabilities were characterized and the table was upgraded to achieve the desired performance of a high fidelity shaking table that can be used for RTHS testing as intended. Due to the experienced uplift at the original table roller supports, a hold-down system was adopted for table upgrade. The original table before upgrade and the table after the full upgrade are shown in Fig. 4.2.

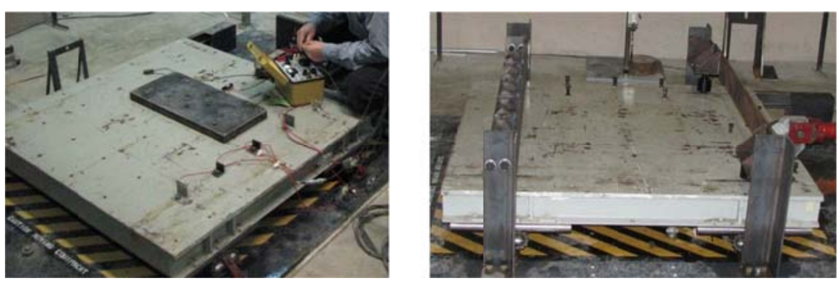


Figure 4.2 Unidirectional shaking table at UC-Berkeley before (left) and after (right) upgrade.

The response of the tested insulator post was compared to the corresponding post response from the as-installed switch test. Achieving a comparable response in both cases was the aim of this effort to move forward to the next step of the development of a RTHS framework to generate the input signal online instead of generating it offline from previous switch tests.

4.2. Test Results

The results of the substructured test used for comparison with as-installed switch tests were obtained at a 20% scale of the full signal measured in the as-installed switch test, and then linearly scaled up to 100% to compare with the as-installed test. The response quantities considered for comparison were the relative displacements of the jaw-side insulator in both PEER and small shaking table tests, shown in Fig. 4.3, and the strains at two opposite sides at the insulator bottom plotted against each other for the two tests in Fig. 4.4. The results show a good match in relative displacements and strains, validating the developed substructuring concept for 230-kV switch.

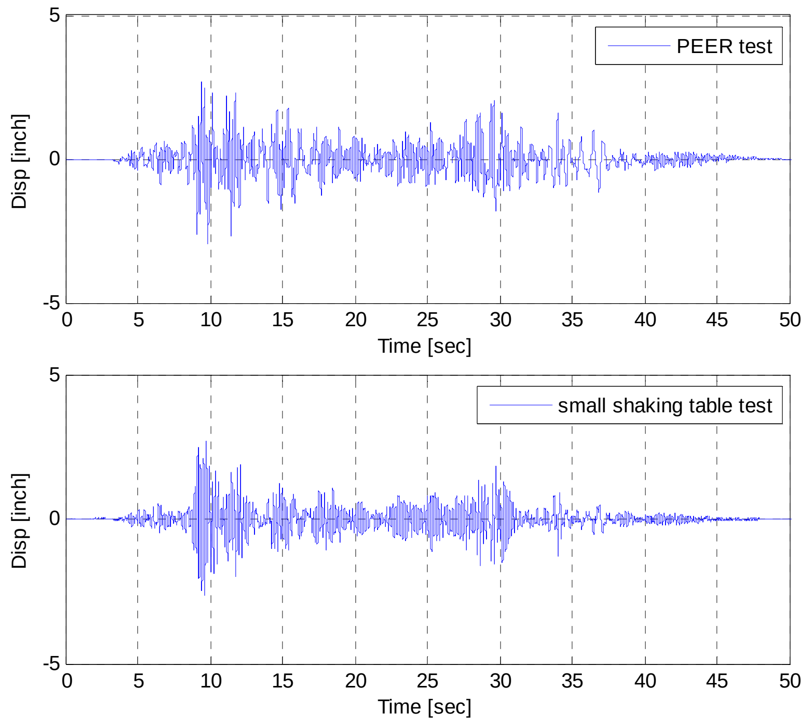


Figure 4.3 Comparison of relative displacements between the top and bottom of the jaw post for the as-installed switch test at PEER shaking table and substructured test at the small unidirectional shaking table.

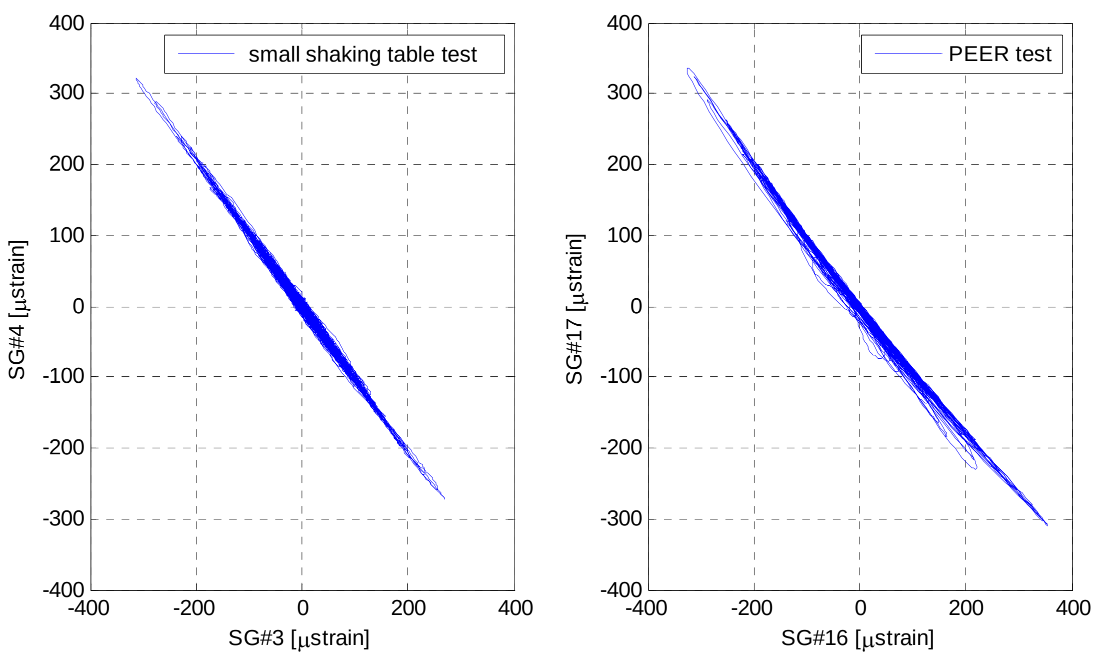


Figure 4.4 Comparison of strains at the insulator bottom for the as-installed switch test at PEER shaking table and single insulator test at the small unidirectional shaking table.

5. HYBRID SIMULATION TESTS

After the 230-kV substructured test was properly validated, it was desired to develop a RTHS framework where an online computed signal is used instead of the offline generated signal used in the substructured tests. An integrated environment that uses a single-degree-of-freedom spring model to represent the support structure (analytical substructure) was utilized along with the single insulator post (physical substructure) to generate and update the input for the small shaking table in real time. Although not presented here, the implementation and validation of the RTHS framework was successfully achieved and details can be found in (Mosalam et al., 2012 and Günay et al., 2012).

6. CONCLUSIONS

From the 230-kV and 550-kV porcelain insulators static tests, it was observed that force-displacement and force-strain relationships are very close to linear until failure. Porcelain insulator posts showed brittle mode of failure in fragility tests as the failure took very short time to develop and propagate.

From the substructured dynamic tests of the 550-kV switches, it was shown that including the rotation component in the input signal resulted in better match with the as-installed switch test. This reflects the significance of the out-of-plane rotations induced at the top of a flexible support structure as it contributes to approximately 25% (for this switch design) of the response quantities during earthquake loading. Accordingly, if the support structure is properly stiffened to eliminate or minimize the rotations, the straining actions developed during earthquakes can be reduced. In addition, rotations cannot be ignored if HS testing that utilizes substructuring is to be conducted.

From the substructured dynamic tests of the 230-kV insulator posts, it was concluded that applying the uniaxial offline generated signal to the single post can reasonably reproduce the response from triaxial shaking table test of the as-installed switch in the open-open configuration. This implicitly validates the assumption that the rotations at the top of the rigid support structure used in the 230-kV switches can be ignored when single insulator post is tested. Accordingly, a HS framework for unidirectional testing of a single post insulator of 230-kV switches installed on stiff frames is a suitable approach.

AKCNOWLEDGEMENTS
The research was supported by California Institute for Energy and Environment, Subcontract TRP-08-02. The authors thank the staff at PEER Center and UC-Berkeley Structures Laboratory for their assistance. Special thanks are due to Southern States, LLC for donating the 550-kV switch assembly and parts of 230-kV switch.

REFERENCES

Chopra, A.K. 2007. Dynamics of Structures: Theory and Applications to Earthquake Engineering. 3rd ed. Prentice Hall: Englewood Cliffs, New Jersey.

Fujisaki, E. (2009). Seismic Performance of Electric Transmission Systems, *Presentation at PEER Annual Meeting*, San Francisco, California.

Günay, M.S., Moustafa, M.A., Mosalam, K.M. 2012. Real Time Hybrid Simulation of Electrical Insulator Posts Using a Smart Shaking Table and Comparison with Full Dynamic Testing. 3rd International Structural Specialty Conference, Edmonton, Alberta, June 6-9.

IEEE Standard 693-2005. Recommended Practice for Seismic Design of Substations. New York NY.: IEEE Standards Department.

Mosalam, K.M., Moustafa, M.A., Günay, M.S., Triki, I. and Takhirov, S. 2012. Seismic Performance of Substation Insulator Posts for Vertical-Break Disconnect Switches. California Energy Commission Publication Number: CEC-500-2012.

Takhirov, S. (2008). Seismic Qualification Report on EC-1, P and EV-1 Types of 245-kV Disconnect Switches with EVG-1 Grounding Switch Installed. *Report No. SS-SCE-2008*, Earthquake Engineering Research Center, University of California, Berkeley.

Takhirov, S. (2011). Seismic Qualification Study of 550-kV Vertical Break Disconnect Switch. *Report No. PEER – STI/2011-02*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.