Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Substation Equip. Interaction - Experimental Models of Flexible Bus Connectors*—**403**		
Start/End Dates	7/1/00 – 12/31/02	Budget/ Funding Source	$160,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Filiatrault (UCSD)**		

1. Project goals and objectives

This project has two main objectives: 1) to investigate experimentally the dynamic interaction between components of electrical substation equipment interconnected by flexible (cable) conductors and 2) to observe experimentally the flexural response of flexible conductors and to determine their moment-curvature relationships under axial tension.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

In response to the vulnerabilities exhibited by substation equipment in recent earthquakes, utilities, manufacturers, and others closely related with the industry have developed new seismic qualification procedures that are described in the IEEE 693 standard. These procedures, however, only qualitatively address the interaction between equipment connected by conductors by recommending that equipment connections be designed and installed to minimize interaction forces. This lack of specificity in the standard is due to the wide variety and complex behavior of equipment used in substations, manufacturer and utility-specific design characteristics of both the equipment and their support structures, and practical considerations of the qualification procedure. For these reasons, electrical equipment items are, in general, seismically qualified in a "stand-alone" condition (i.e. without connection to the adjacent equipment). Analytical studies have suggested that bending properties of flexible conductors might affect the behavior of short jumpers and some "long" conductors. Limited dynamic interaction experiments involving equipment models interconnected by flexible conductors have been performed to evaluate the importance of this dynamic interaction effect. The results generated in this project shed further light on this issue by characterizing the seismic response of substation equipment interconnected by flexible conductors.

3. Brief description of the accomplishments of the project

Based on the results of the shake table tests performed in this study on five different pairs of generic equipment connected by three different types of flexible connector assemblies, the following conclusions can be drawn:

- For large slackness, the fundamental frequencies of the equipment items were not affected significantly by the presence of the flexible conductor assemblies.
- The presence of the conductor assemblies increased significantly the damping ratios of interconnected equipment.
- No damage to any of the three flexible conductors was observed during all the seismic tests conducted.
- For all slackness values, the dynamic response of the most flexible equipment is not affected very much by any of the three flexible conductors tested.
- At large slackness, the dynamic response of the most rigid equipment is generally reduced by the presence of the conductor assemblies.
- At large slackness, the forces generated at the top of the interconnected equipment are small. In most cases, the force at the top of the most flexible equipment is larger than the force at the top of the stiffer equipment.
- At small slackness, the dynamic response of the rigid equipment can be significantly increased once the conductor assemblies become tight and act as tension-only springs. This amplification of the dynamic response increases with the intensity of the ground motion.
- At small slackness, the forces generated at the top of the interconnected equipment are an order of magnitude higher that that measured at 5 and 10% slackness. For this slackness, the forces at the top of both interconnected equipment specimens are similar.

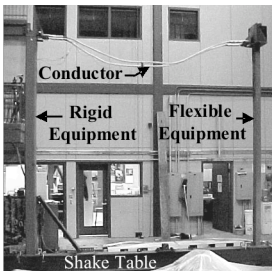
The results obtained from the quasi-static bending tests performed on two different full-scale flexible conductors (cables) indicate that the global force-displacement behavior of both conductors is linear-elastic with negligible hysteretic response. For most combinations of axial tension and lateral conductor displacement, the flexural stiffness exhibited by both conductors is very small, and tends toward the minimum possible flexural stiffness, corresponding to the situation where all the strands are slipping past each other, and are unable able to transfer any shear force. Only for very large axial tension values (more than 4.5 kN or 100με that the flexural stiffness of the conductors approach the maximum possible flexural stiffness, corresponding to the situation where all the strands are able to transfer longitudinal shear forces over one another, and the conductor section acts as a solid cross-section. It is unlikely that such high axial tension values can be mobilized during the seismic response of interconnected substation electrical equipment.

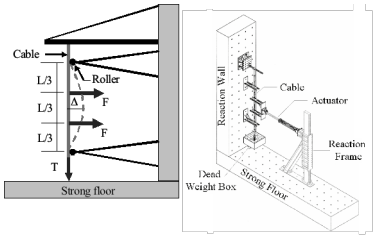
4. Describe any instances where you are aware that your results have been used in industry

The results generated in this study are being considered by IEEE-693 Committee for future editions of their standard.

5. Methodology employed

In the first part of the study, shake table tests of five pairs of generic substation equipment interconnected by three different flexible conductors with three different levels slackness were performed to evaluate the influence of different conductor assemblies on the structural dynamic response of interconnected substation equipment components. Simulated horizontal ground motions were applied in the longitudinal direction of the bus assemblies by a uniaxial shake table. In the second part of the project quasi-static bending tests performed on two different full-scale flexible conductors (cables). These tests were performed in transverse direction of the conductor assemblies under prescribed axial tension and displacement time history. The main objectives of these quasi-static tests were to observe the flexural response of flexible conductors and to determine their moment-curvature relationships under various axial tension values.





6. Other related work conducted within and/or outside PEER

This project was conducted in close collaboration with an analytical project on the same topic conducted at the University at California, Berkeley.

7. Recommendations for the future work: what do you think should be done next?

The experimental study conducted herein represents only a first step in fully understanding the seismic interaction between interconnected substation equipment. Future research is needed to expand the experimental studies to multi-span equipment/conductor layouts and multi-axis ground motion input. Furthermore, simplified analysis tools need to be developed in order to consider interaction effect at the design stage of interconnected substation equipment.

8. Author(s), Title, and Date for the final report for this project

Filiatrault, A., and Stearns, C., Electrical Substation Equipment Interaction–Experimental Flexible Conductor Studies, February 2003.