Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Substation Equipment Interaction -- Analytical Modles of Flexible Bus Connectors*—**403b**		
Start/End Dates	7/1/00 – 12/31/02	Budget/ Funding Source	$100,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Der Kiureghian (UCB)**		

1. Project goals and objectives

This project aimed at developing a better understanding of the mechanical behavior of conductor cables (flexible bus) and the dynamic response of equipment items connected by such conductors. In particular, the effect of interaction between equipment items were to be quantified and the necessary conductor slack to reduce this adverse effect was to be determined, while accounting for the stochastic nature of ground motions.

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.

The results of the project have provided an improved understanding of the mechanical behavior of conductor cables, which are formed by helically wrapped aluminum wires. The model properly accounts for the effect of wire slippage under friction forces. This model has been implemented in a finite element code for dynamic analysis of cable-connected equipment items, accounting for material and geometric nonlinearities. This novel model and analysis approach allows accurate prediction of the behavior of substation equipment items connected by flexible bus and subjected to earthquake loading. Furthermore, design rules are provided to determine the required conductor slack in order to reduce the adverse effect of interaction on the equipment items to a manageable level. These results will help reduce the seismic vulnerability of electrical substation equipment connected by flexible bus conductors.

3. Brief description of the accomplishments of the project

A theoretical model is developed to describe the nonlinear moment-curvature relationship of conductor cables composed of helically wrapped aluminum wires. The model accounts for the friction and slippage that occurs between wires in neighboring layers when the cable is bent. A first-order differential condition for slippage of wires is derived by noting that a wire slips if the unbalanced tension force in a differential element of the wire, which is caused by bending, exceeds the maximum friction force on the wire that can be generated. The wire remains in a stick state if the unbalanced tension force is less than the maximum friction force that can be generated. In each cross section of the cable, two regions are identified: a region of stick and a region of slip. In the stick region, the continuity of axial strain in each wire along with the Bernoulli-Euler-Navier kinematic beam assumption are used to determine the axial force in the wire. In the slip region, the condition for the slippage of wires is used to determine the axial force in each wire. The resultant moment of the cable is nonlinearly related to the curvature of the cable; this nonlinear relationship also depends on the axial strain (or axial force) in the cable. Accordingly, the bending stiffness of the cable nonlinearly varies between two extreme limits. These correspond to the extreme cases of fully slipping and fully stuck wires. The difference between the two stiffnesses can be as large as two orders of magnitude. Figure 1 shows the moment-curvature relations for a specific conductor cable for two values of the friction coefficient and selected values of the cable tension force.

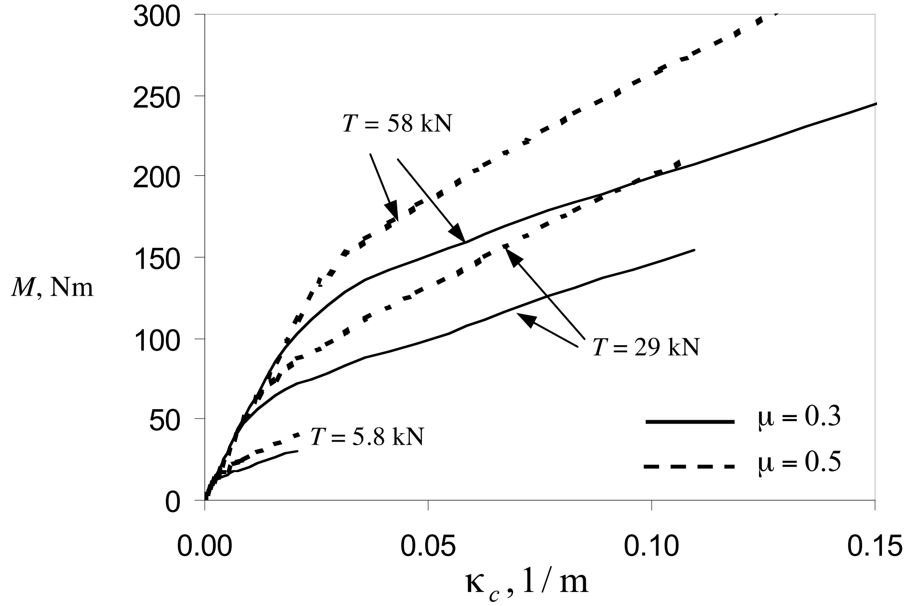

Figure 1. Moment-curvature relations of Jessamine conductor cable for two values of friction coefficient and selected cable tension force

A finite element model for the cable is developed by using a geometrically exact rod model and fitting the nonlinear moment-curvature-tension relationship of the cable with a bilinear elasto-plastic constitutive model. Kinematic hardening is assumed to represent the nonlinear bending behavior of the cable. Comparisons are made between predictions by the finite element model and tests conducted by other investigators under static and dynamic conditions.

The finite element model developed is used to investigate the effect of dynamic interaction between two idealized equipment items connected by a conductor cable and subjected to ground motion. It is shown that the dynamic cable force can be significantly larger than the cable force under static equilibrium conditions. Furthermore, it is shown that the equipment response in the connected system can be strongly amplified relative to the response of the stand-alone equipment, particularly for the equipment item having the higher frequency. A simple predictive formula to estimate the amplification of equipment response due to the interaction effect is developed, and a practical design rule for selecting the cable slackness to limit the interaction effect in the cable-connected system is derived.

Figure 2 shows the effect of interaction on the higher-frequency equipment item in a pair of equipment items connected by the Trillium conductor cable. The effect is shown as an amplification factor in the response of the equipment, relative to its stand-alone response, as a function of an interaction parameter that depends on the conductor slack. Results for five ground motions are shown. It can be seen that the amplification in the equipment response as a result of the interaction effect can be very significant.

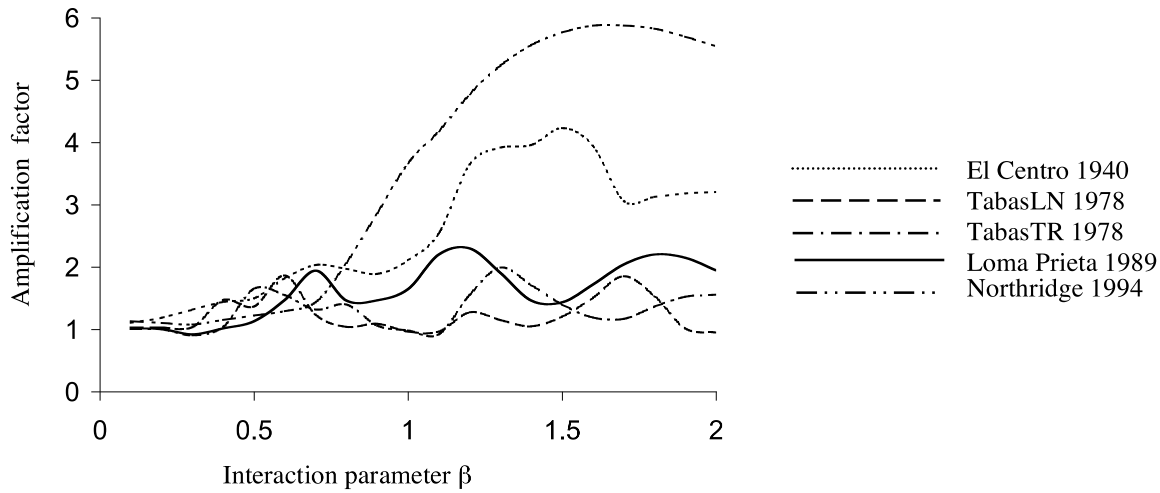

Figure 2. Effect of interaction in higher-frequency equipment item for selected ground motions.

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

We are not aware that our results have been used by the industry at this time. However, we are aware that power company engineers have shown strong interest in our results.

5. Methodology employed

We used continuum mechanics to develop the model for the bending behavior of the conductor cable. This model was then implemented in an existing finite element code (FEAP by R. L. Taylor) by use of an exact rod element that accounts for large displacements and rotations. A time integration method was then selected, which is capable of dynamic analysis with material and geometric nonlinearities. The finite element code was used to simulate the response for a large number of example cable-connected equipment systems. Comparisons were made with experimental data. Finally, the numerical simulations were used as virtual data to fit a statistical model to predict the interaction effect as a function of system characteristics and the cable slack. This model was used to derive a design rule for the required slack in order for the amplification factor to remain below a specified threshold.

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

Experimental work parallel to this study was conducted at UC San Diego by Professor A. Filiatrault. Comparisons between the experimental results and analytical predictions based the model developed are presented in this study.

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

The model developed for the conductor cable assumes motions in a vertical plane. This is adequate for analysis of seismic interaction between two connected equipment items, since the interaction then primarily happens in the plane of the conductor. It would be beneficial to extend the model to 3 dimensions. Such a model would be necessary to investigate the dynamic response of transmission lines and other cable structures under wind, ice and earthquake loading, or their combinations.

Our investigations also showed that further experiments under well controlled environment are needed to better understand the hysteretic behavior of the helically wrapped conductor cable under bending and axial force, so as to provide a basis for the validation and calibration of analytical models. Experiments to determine the interlayer friction coefficient between the wires in conductor cables is also needed.

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

Kee-Jeung Hong, Armen Der Kiureghian and Jerome L. Sackman, "Dynamic Interaction in Cable-Connected Equipment," Spring 2003.