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SEISMIC INTEGRITY OF INSULATED CONDUCTORS

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SUMMARY

In recent years, a concern has been raised in the U.S. nuclear industry regarding the seismic performance of electrical cable and flexible conduit: the basic issue is relative displacement effects at the transition points in electrical systems. In order to address this issue, a sampling program was used to evaluate as-built condition. A physical inspection and detailed engineering evaluation of 375 raceway transitions indicated that there is no systematic deficiency in current cable installation procedures. The inherent flexibility of the cable and conduit, combined with standard cable pulling and training requirements, are sufficient to ensure the seismic integrity of insulated conductors.

INTRODUCTION

Seismic considerations have come to play a major role in the design of almost all components in nuclear power plants. In the case of insulated conductors, however, the current industry standards (e.g., allowable pulling tensions, minimum bend radii, fire protection criteria, etc.) do not include any provisions for seismic adequacy. The lack of a seismic design basis has led to some concern in the U.S. nuclear industry-primarily with respect to the relative displacement effects that can occur at the transition points in the electrical systems. If an electrical cable is physically damaged or pulled out of a terminal, it could render a safty-related system inoperable.

Some nuclear utilities and architectural/engineering firms have attempted to address the seismic adequacy question by including a "slack" requirement in cable installation procedures; i.e., by specifying that a particular amount of slack be built into each transition point in the electrical systems. These attempts have proven troublesome, however, in several respects. In the first place, there is little engineering basis for a quantified slack requirement; the relative displacement that will occur at any given transition is generally unknown, as is the minimum slack required to ensure system integrity. Even if this information were available, it is often difficult to provide a specific amount of slack at transition points - partiularly those involving a large number of cables. From a QC perspective, it can be difficult to measure slack in the field and, given the tendency for cables to contract somewhat after pulling, there is no assurance that the slack provided will remain in the transition.

Insulated conductors are inherently flexible and earthquake experience to date does not indicate any significant problems with seismic performance. Given these facts, and the considerable difficulties associated with explicit slack requirements, the question naturally arises as to whether or not these requirements are really necessary. The objective of the study reported herein was to evaluate the seismic performance of insulated conductors and determine what seismic design and installation criteria - if any - are necessary to ensure functional integrity.

NOMENCLATURE

A	Cross sectional area of copper conductor	ε	Strain in cable at a transition
E	Young's modulus of copper conductor	θ	Contact angle
Δ	Relative displacement between transition points	μ	Coefficient of friction on cable
L_e	Effective length of a cable	S	Available Slack

METHODOLOGY

The evaluation was carried out within the framework of an acceptance sampling program. A 95/95 screening criteria was used for the detection of systematic deficiencies (i.e., if a randomly selected sample of items is found to be acceptable, it can be stated at the 95% confidence level that at least 95% of the total population is also acceptable, and there is no generic problem). The "inspection item" in this study was defined as all electrical cable within any given transition. A transition is defined as the region where cables pass from one component of the electrical system to another (e.g., a cable tray to conduit "transition").

Based upon the cable pulling schedule for the plant studied, there are approximately 5350 safety-related transitions where non-trivial relative displacement effects might occur during an earthquake. Of these, approximately 4200 are air-drop transitions (i.e., unprotected cables), and 1150 are flexible conduit transitions (i.e., protected cables). For sampling purposes, the air-drop transitions were divided into four homogeneous sub-populations: 1) Cable Tray to Cable Tray, 2) Cable Tray to Conduit, 3) Cable Tray to Equipment, and 4) Building to Building. The homogeneous sub-populations for flexible conduit transitions were defined as: 1) Building to Building, and 2) Raceway to Pipe-mounted Equipment.

A minimum of 60 samples were evaluated for each sub-population (except for building to building flexible conduit transitions, of which there were a total of 30, and all were evaluated). Each of the randomly selected transitions was inspected in the field to determine the geometry of the transition, the number and type of cables involved, the amount of slack in the transition, raceway and equipment details, etc. The as-installed conditions were used for an evaluation of seismic adequacy with respect to the design basis earthquake for the plant.

Air-Drop Transitions For the sake of efficiency, the evaluation of air-drop transitions was carried out using a multi-step screening process. In the first step, generic analyses were performed to develop conservative estimates of the maximum, three-dimensional relative displacements that could occur at the various types of transitions. These upper-bound values were then compared with the as-measured slack that was available in each of the sampled transitions. If the available slack was greater than the upper-bound generic displacements, the transition was deemed acceptable and no further evaluation was required; 37% of the air-drop transitions were qualified in this first step.

The second level of screening was similar to the first except that, in this case, more refined, transition-specific displacements were used. An additional 50% of the air-drop transitions were qualified in this step; i.e., there was sufficient slack in the transition to accommodate any relative displacement effects that might occur during an earthquake.

For the remaining 13% of the transitions, the imposed displacements could be greater than the available slack and, hence, could induce tensile forces in the electrical cables. The third level of screening was an evaluation of upper-bound cable forces; the transition was deemed acceptable as long as the tension did not exceed the manufacturer-specified allowable pulling tension for the cables.

Cable forces were computed in one of two ways depending upon the stiffness of the cables relative to the stiffness of the cable restraint points. Where the cable stiffness was negligible - as in a building-to-building transition - the forces were determined based upon the strain induced in the cable. The strain, ε, will be a function of the imposed displacement, Δ, the available slack, S, and the effective length of cable, L_e, between restraint points. That is:

$$\varepsilon = \frac{\Delta - S}{L_e} \tag{1}$$

The effective length of cable is computed as the actual distance between restraint points or by accounting for the partial restraint provided by frictional forces. In practice, the only significant frictional forces(during the vibratory motion of an earthquake) will be those occuring around bends in the raceways. Assuming a constant tension in straight portions of the raceway, and an exponential decrease in tension around each bend, the effective length of cable over which the net displacements must be accommodated may be obtained from

$$L_e = L_1 + L_2 e^{-\mu\theta_1} + L_3 e^{-\mu(\theta_1 + \theta_2)} \tag{2}$$

where L_i is the length of the i^{th} raceway segment, μ is the coefficient of friction between the raceway and the cable, and θ_i is the angle change around the i^{th} bend in the raceway (see Figure 1). Given the effective length of cable, and the resulting strain from Eq. (1), the corresponding cable tension is given by

$$F = EA\varepsilon \tag{3}$$

where E is the modulus of elasticity of the copper conductor, and A is the cross-sectional area of the conductor. Only the most critical cables in each transition need to be analyzed; i.e., the ones with the least slack and smallest lengths. If the forces computed from Eq. (3) are less than the allowable pulling tension, the transition is acceptable.

For those transitions involving large bundles of cable and/or relatively flexible raceways, the cable can introduce a stiffness coupling across the transition. In these cases, a nonlinear 2-degree of freedom dynamic model was used to compute the forces in the cables. The model (Figure 2) includes the three-directional dynamic characteristics of the raceway on each side of the transition, where Guyan reduction techniques are used to obtain the two equivalent degrees of freedom. The coupling spring and gap between the two mass points are based upon the number and type of cables in the transition, their effective lengths as discussed above, and the amount of slack initially present in the transition.

It may be noted that the nonlinear model shown in Figure 2 explicitly accounts for the "snap" effect that occurs when slack cables are suddenly pulled taut during an earthquake. This impact-type loading can produce relatively high cable forces. Figure 3 shows some example results and illustrates the influence of some of the parameters affecting the dynamic behavior of the raceway transitions. As before, if the maximum forces in the cables were less than the allowable pulling tensions, the transitions were deemed acceptable.

For those air-drop transitions involving equipment, the cable was assumed to be fixed at the environmental seal where the cable entered the equipment. This assumption maximized the forces on both the cable and the equipment and, hence, was conservative. It also eliminated the possibility of any computed forces on the terminations, however. In order to address this point, the amount of slack available inside the equipment was also measured and was found to be substantial (as would be expected based upon standard cable training requirements). The total amount of slack in the transition and inside the equipment was always greater than the imposed relative displacements between the raceway and the equipment. In practice, therefore, the environmental seal might be damaged but not the electrical termination; the functional integrity of the equipment itself would not be jeopardized.

<u>Flexible Conduit Transitions</u> Flexible conduit is comprised of interlocking spiral links, each portion of which can accommodate a small amount of deformation (with negligible resistance) before it "locks up". Further deformation tends to kink and unravel the conduit and could damage the cable within. The acceptance criteria for flexible conduit transitions, therefore, was relatively straightforward and conservative; the flexible conduit transitions were considered adequate if the built-in deformation capabilities of the conduit were able to accommodate the entire relative displacements imposed on the transitions. Restated, the transitions were acceptable if the flexible conduits "locked up" along less than or equal to 100% of their length.

Flexible conduit can lock up in either a compression/bending mode, or a tension/bending mode, depending upon the geometry of the transition and the nature of the imposed displacements. Typical configurations are shown in Figures 4 and 5. A computer program was developed to evaluate the behavior of each sampled transition given the actual displacements for that transition.

The initial geometry of the flexible conduit was used as a starting point and incremental displacements were applied to the end points. As portions of the conduit reached minimum bend radius or maximum elongation, they were locked up and displaced as rigid bodies for all further movement. The incremental analysis continued until all segments of the conduit were locked up or until the entire relative displacement was accommodated.

RESULTS

A total of 375 randomly selected transitions were evaluated using the methodologies described above. All were found to be acceptable in their as-installed condition. In approximately 90% of the cases, the imposed seismic displacements (or combined seismic and thermal displacements in the case of pipe-mounted equipment) were less than the available slack in the transition. In the remaining cases, some force might be exerted on the electrical cables but it was always less than the allowable cable pulling tension as specified by the cable manufacturers.

Given the information gathered during the plant walkdowns for this project, and the experience gained during the evaluation stage, it was possible to postulate some reasonable worst-case conditions that might exist in the unsampled population. These were also evaluated using the methodologies described above, or variations thereof. This adverse trends analysis suggests that there is probably a large factor of safety in the transitions - even under the most severe conditions. The factor of safety is difficult to quantify, however, because the real operability limits for insulated conductors are not known. The acceptance criteria used in this study are believed to be very conservative with respect to the true functional capacity of the cables.

CONCLUSIONS

The results of this study suggest that, with respect to seismically induced loadings and displacements, there are no systematic deficiencies (95/95 screen) in current installation practices for electrical cable and flexible conduit. New criteria specifically related to slack at raceway transition points would be difficult to formulate and apply, and appear to be unnecessary. Current industry standards dealing with minimum bend radii, maximum pulling tensions, cable training requirements, etc., appear to be adequate to ensure the seismic integrity of insulated conductors, terminations, and equipment. With the possible exception of building-to-building transitions, the results of this study should be applicable to most other nuclear plants as well.

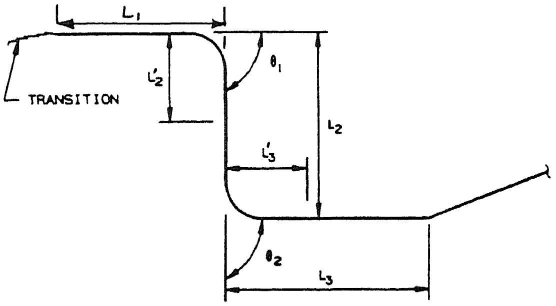


Fig. 1 Plan view of cable routing in tray-to-penetration sleeve transition (building-to-building)

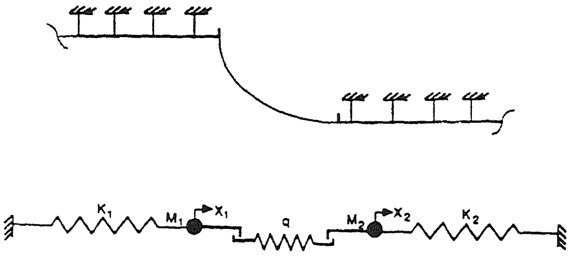


Fig. 2 Dynamic model used to investigate snap effect.

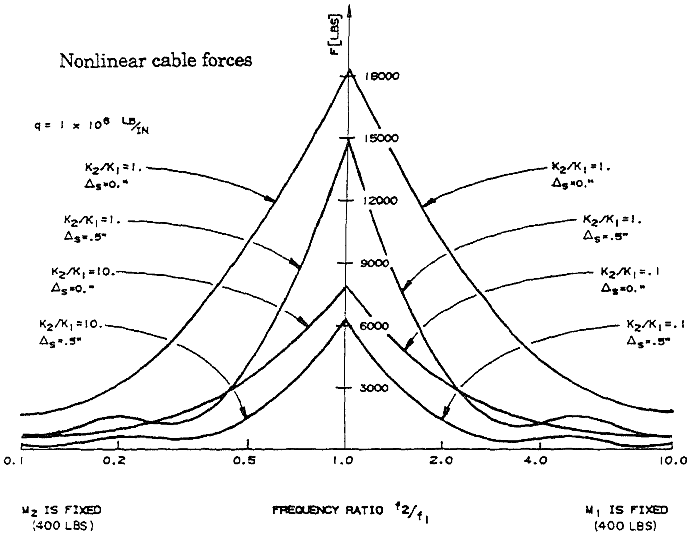
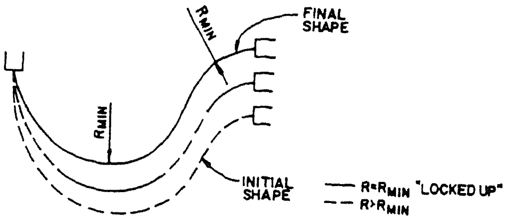


Fig. 3 Nonlinear cable forces.



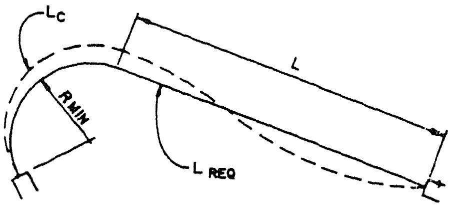


Fig. 4 Compression mode.

Fig. 5 Tension mode.