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Reconciliation of Experimental and Analysis Results for Electrical Cabinets in Nuclear Power Plant

Parth Patel[1], Abhinav Gupta[2], Sung Gook Cho[3]

[1]Doctoral Student, CCEE, North Carolina State University, USA (papatel9@ncsu.edu)
[2]Director, Center for Nuclear Energy Facilities and Structures, NCSU, USA
[3]R&D Center, Innose Tech Co. Ltd., Republic of Korea

ABSTRACT

Traditionally, electrical cabinets in a nuclear power plant are seismically qualified by conducting shake table tests and comparing the in-cabinet response spectra (ICRS) with the capacity of instruments inside the cabinet. During shake table testing, the cabinet is usually mounted on a shake table using some additional mounting structures such as plates and frames with channel and angle sections. The current study focuses on exploring the effect of these additional mounting structures on the seismic behavior of an electrical cabinet and its ICRS. In this study, a nonlinear finite element (FE) analysis of a cabinet with a tubular base is carried out to generate ICRS. The comparison of FE results with the experimentally generated ICRS shows that the addition of mounting structures makes a large impact on the generation of ICRS.

INTRODUCTION

In a nuclear power plant (NPP), electrical cabinets and control panels are one of the most critical equipment for maintaining the safety of the plant during a seismic event. To assure the safe shutdown of the NPP during a seismic event, it is necessary for electrical instruments located inside a cabinet to operate as intended. Failure of instruments in a cabinet can lead to an emergency or an accident condition. A robust seismic qualification of cabinets is typically conducted by shake table testing and generating in-cabinet response spectra (ICRS) (Di Sarno et al., 2019; Gupta et al., 1999b; Rustogi and Gupta, 2004). The ICRS shows the dynamic response of the cabinet at various locations where the electrical instruments are located (Gupta et al., 2019). Subsequently, instruments are qualified by a shake table testing of the instruments by using ICRS as the seismic input (ASCE, 2000; ICC, 2010). The electrical instruments are considered to be seismically qualified if the ICRS lies below the capacity of the instruments inside the cabinet. Performing shake table tests for every electrical cabinet in the nuclear power plant is both time and cost-intensive (Gupta et al., 2019). An alternative is to perform a FE analysis of the cabinet. To validate the FE model, reconciliation of the experimental result with the FE analysis result is necessary (Jeon et al., 2021). Studies (Gupta et al., 1999a; Gupta and Yang, 2002; Singh and Gupta, 2021; Yang and Gupta, 2001) show that the most significant mode of deformation in a cabinet can either be a pure rocking mode or a global rocking mode combined with local bending mode of the panel. The dynamic behavior of the cabinet in the rocking mode is primarily dependent on the rocking stiffness of the cabinet (Yang et al., 2003). The variety of the base and the arrangement of the mounting structures significantly affect the rocking stiffness of the cabinet which eventually plays a vital role in the dynamic behavior of the cabinet.

In this paper, a detailed FE model of a cabinet with a tubular base used for the shake table test is modeled. The FE modeling and the nonlinear time history analysis of the cabinet are performed in ABAQUS software (ABAQUS, 2021). During the experiment, the cabinet is not directly mounted on the shake table.

Instead, an additional channel and a base plate are used to mount the cabinet to the shake table. These additional structures are assumed to be very rigid with no influence on the test results. The additional structures are added in the shake table test for the stability of the cabinet during the test even though they are not present in an actual nuclear power plant.

DESCRIPTION OF SHAKE TABLE EXPERIMENTS

In 2018, Innose Tech of Korea performed multiple shake table tests of an electrical cabinet used in a nuclear power plant. The test cabinet has seven accelerometers (G1 to G7) mounted at different locations on the cabinet to record the acceleration time history response. Figure 1 shows the schematic of the electrical cabinet used in the shake table test. The accelerometers are mounted at different elevations of the cabinet, as shown in the Figure 1. The test cabinet has a width and depth of 800 mm $\times$ 750 mm with a height of 2100 mm. The main frame of the cabinet consists of six vertical members having a tubular cross-section. At the top and base of the cabinet, the vertical members are welded with the horizontal members in a rectangular shape. In addition, the test cabinet also contains internal frame members with bolted connections, four shelves, and 2 doors with stiffeners.

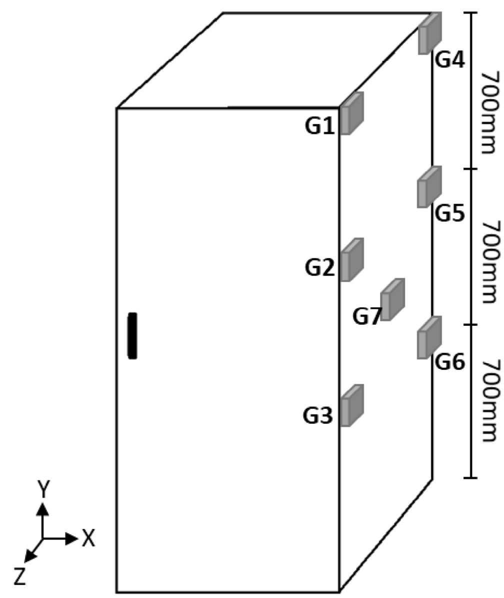
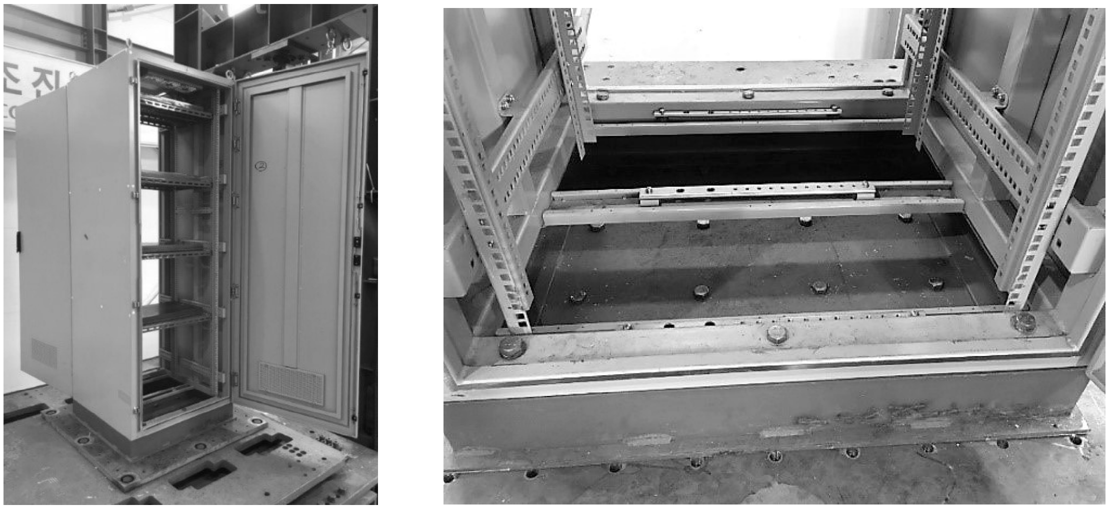


Figure 1. Accelerometers mounted on test cabinet

The base of the test cabinet contains a rectangular frame with four members of a square tubular section. The tubular base is connected to the floor with six anchor bolts. Two additional structural members are also added below the base of the cabinet, as shown in Figure 2, to provide additional stability to the cabinet during testing. The tubular base of the cabinet is connected with a channel section with a subsequent base plate. Finally, in the test setup, the base plate is connected to the shake table using 16 anchor bolts.



(a) Test Cabinet (b) Mounting arrangement

Figure 2. Test setup for shake table experiment

In the shake table testing, three test setups are considered by changing the weight that is used to represent the equipment inside the cabinet. Figure 3 shows the cabinet with added weights and their locations for the three different test setups. The cabinet weighs 287 kg and no additional weight is considered for the first test setup, whereas for the second and third test setups, 100 kg and 200 kg of added weights are considered respectively. The “EL Centro” earthquake data is used as input to the shake table testing. The responses in the form of acceleration time history are recorded at all the seven accelerometers for each case. To reconcile these test results, FE approach is employed to model and analyze the cabinet as discussed in the following sections.

(a) Case 1: 287kg Weight (b) Case 2: 387kg Weight (c) Case 3: 487kg Weight

Figure 3. Test setup for different cases

CABINET MODELING

As mentioned in the previous section, the electrical cabinet used in the experiment is mounted on a shake table using an additional channel section and a base plate. Therefore, to explore the effect of these additional structures on the dynamic responses of the cabinet, three FE models are modeled based on the different structural members at the base of the cabinet. The details of these three FE models are elaborated in the following subsections.

First modeling approach: Base Tube only

In the first modeling approach, no additional structures are considered at the base of the electrical cabinet. The dynamic behavior is observed for the cabinet anchored directly to the floor. Moreover, the first modeling approach represents the actual condition of a cabinet in a nuclear power plant. Figure 4 shows the modeling of the electrical cabinet without additional mounting structures. The main frame and the internal frame of the cabinet are modeled using 2-noded linear beam elements. Whereas the wall, door panels, and the tubular base are modeled using 4-noded doubly curved shell elements. The connections between all the individual elements are defined using point and line constraints.

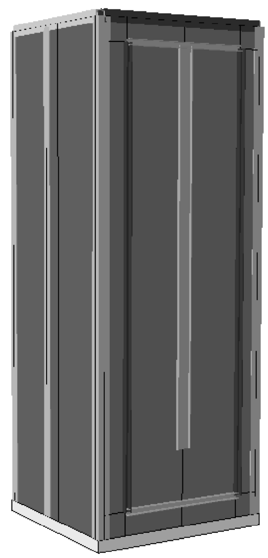


Figure 4. Modeling only cabinet without additional mounting structures

The tubular frame at the base of the cabinet has six holes each at the top and bottom of the tube for anchoring with six bolts. These twelve holes are constrained in three translations and two rotational degrees of freedom. However, these boundary conditions are not sufficient to correctly define the cabinet base. Because a part of the cabinet base can still deflect downwards below the floor level during the rocking motion of the cabinet which is unrealistic. Therefore, compression-only nonlinear springs are applied at all four corners of the cabinet base. The compression-only springs provide high resistance under compression and no resistance in tension. The Young's modulus and the Poisson's ratio of the steel cabinet are 209862.31 MPa and 0.285, respectively. The plastic behavior of the steel material is defined using the bi-linear stress-strain curve considering the yield and ultimate strength of steel to be 345 MPa and 450 MPa, respectively. Based on the sizes and anticipated distortions of the structural components of the cabinet, the mesh sizes of the FE model of the cabinet range from 50 to 250 mm. Since distortion is expected to be more significant near the bolt locations, the base of the cabinet is finely meshed compared to the other part of the cabinet.

The earthquake acceleration time history is applied at the base tube of the cabinet model in the side-to-side direction using an acceleration boundary condition. The nonlinear time history analysis is performed using the direct integration method. The FE software ABAQUS uses Hilber-Hughes-Taylor (HHT) time integration to solve the equation of motion which is an extension of the Newmark beta-method of time integration (ABAQUS, 2021). Rayleigh damping is implemented for the damping ratio of 2%. The nonlinear time history analysis is performed on cabinet models for a total time span of 57.5 seconds with a time step of 0.001 seconds. The elements are meshed in such a manner that the accelerometer location lies on the nodes of the mesh. Extracting the time history data at these nodes after the analysis gives the results that can be directly compared with the test results.

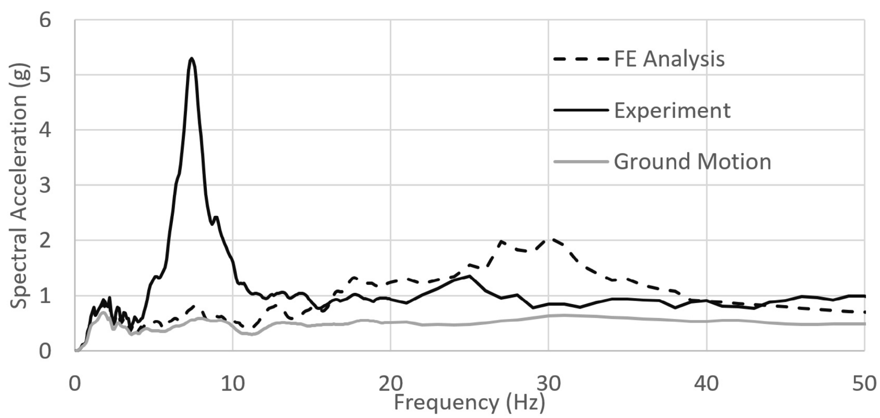


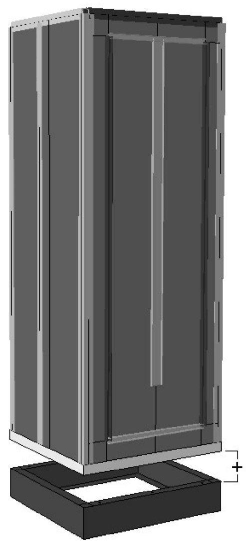
Figure 5. Response spectrum comparison at G1 accelerometer using first modeling approach

The acceleration time history responses are used to generate response spectrum curves. The comparison of the response spectrum plot developed for the FE result along with the test result is shown in the Figure 5. The response spectrum curves are generated based on acceleration time history recorded at the G1 accelerometer location (as shown in Figure 1). The response spectrum of the actual earthquake motion for the El Centro earthquake is also plotted in Figure 5. It can be clearly seen from the comparison that the test response shows a peak near the frequency of 8.8 Hz with a magnitude of 5.3g, whereas, the FE response shows the highest peak around the frequency of 30 Hz with a magnitude of 2g. From the Figure 5, it is evident that the first modeling approach is not able to capture the correct responses of the electrical cabinet as it does not show any mode near the frequency of 8.8 Hz. Moreover, the modal analysis of the cabinet does not show any rocking mode.

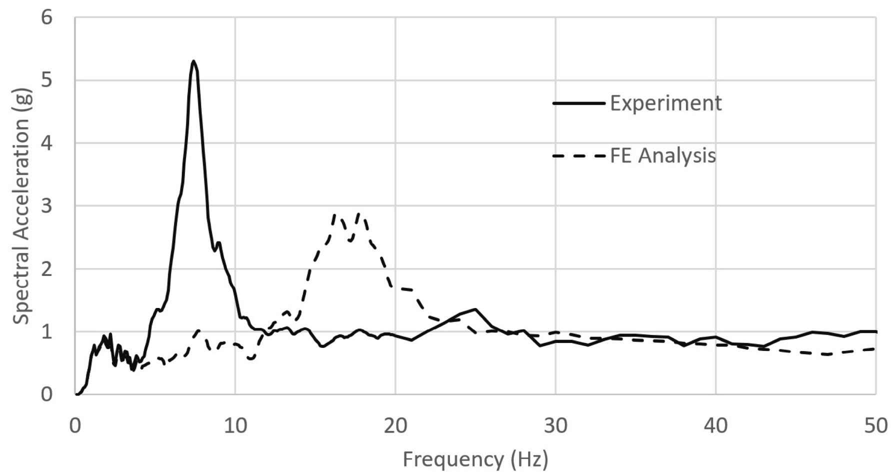
Updated Modeling Approach: Base tube and Channel section

In the updated modeling approach, the additional channel section is added below the tubular base of the cabinet. The key purpose of this approach is to visualize the difference in the behavior of the cabinet after the cabinet base is anchored to the channel section instead of anchoring it directly with the shake-table. Figure 6a shows the modeling of the cabinet having an additional channel section at the base. The anchor holes of the tubular base of the cabinet are connected to the anchor holes of the channel section. The compression-only nonlinear springs at the corners of the tubular base are connected with the corners of the top of the channel. This restricts both the tubular base and the added channel from overlapping. The base of the added channel is restricted from deflecting below the floor level using compression-only nonlinear springs as described earlier.

The FE model is analyzed by performing nonlinear time history analysis to generate the results in terms of the acceleration time history. The acceleration responses at the G1 accelerometer location are used to compare the FE result with the test result. Figure 6b shows the comparison of response spectra between the experimental and simulation response. From Figure 6b, it can be seen that the maximum response for the simulation result is recorded near the frequency of 16.5 Hz with an amplitude of 2.8 g. The modal analysis also shows a rocking mode near a frequency of 16.5 Hz. Thus, the updated modeling approach performs better than the first modeling approach, but it is still very far from predicting a comparable response. Moreover, the plot clearly shows the difference in the acceleration response because of the addition of a rigid seeming channel section to the electrical cabinet. However, to achieve even better responses, another additional mounting structure is modeled in the following approach.



(a) Cabinet model



(b) Response spectrum comparison at G1 accelerometer

Figure 6. Modeling cabinet with additional channel section

Reconciled modeling Approach: Base tube, Channel section, and Base plate

In addition to the channel section, the cabinet in the this approach is modeled using an added base plate below the channel section (Figure 7). The additional base plate provides more stability to the cabinet while mounting it to the shake table. This approach completely replicates the actual shake table test conditions used in the experiments where both additional structures, channel and base plate are present in between the cabinet base tubes and shake table.

The connection between the tubular base of the cabinet and the added channel section is similar to the updated modeling approach, but the connection between the channel and base plate needs a more careful definition. In the experiment, the channel and base plate is welded at the outer perimeter of the base of the channel section. Moreover, the base plate is also connected with the shake table through 16 anchor bolts. For the FE model, line constraints at the weld locations are defined for all six degrees of freedom. The base plate is constrained in five degrees of freedom at all 16 bolt locations. These boundary conditions are not enough to restrict the overlapping of the deflected channel and base plate. Since the base plate can deform in a random manner as it is restrained at 16 locations, therefore, defining compression-only nonlinear springs between channel and base plate at few locations cannot guaranty the no overlapping of both the structures. Hence, a surface interaction between the surface of the base of the channel and the top of the base plate is defined. It the penalty-based friction method with a friction coefficient of 0.3 to maintain no overlap between the structures. The penalty-based friction method transfers the forces using a spring-damper model. Even after providing these constraints, the base plate can still deflect below the floor level and give unrealistic deformation. Therefore, to avoid such undesirable deformation, an additional rigid plate is added below the base plate. This added rigid plate is constrained at 16 bolt locations with the base plate. Finally, a surface interaction is defined between the base plate and the rigid plate to restrict the base plate from deflecting downwards and keeping it free to deflect upwards.

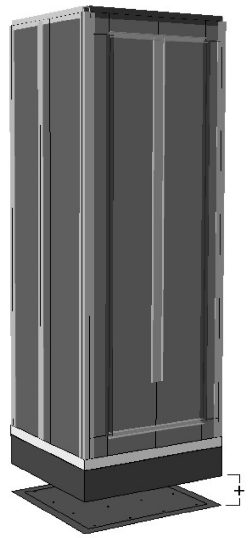


Figure 7. Modeling cabinet with added channel and base plate

The nonlinear time history analysis under earthquake ground motion is performed to analyze the current model. The acceleration time history data from the analyzed model at G1 location are extracted to compare these responses with the corresponding test result. Figure 8 shows the comparison of acceleration time history response at G1 location. Looking at the comparison, it can be inferred that the current model is able to mimic the acceleration time history response of the experiment correctly.

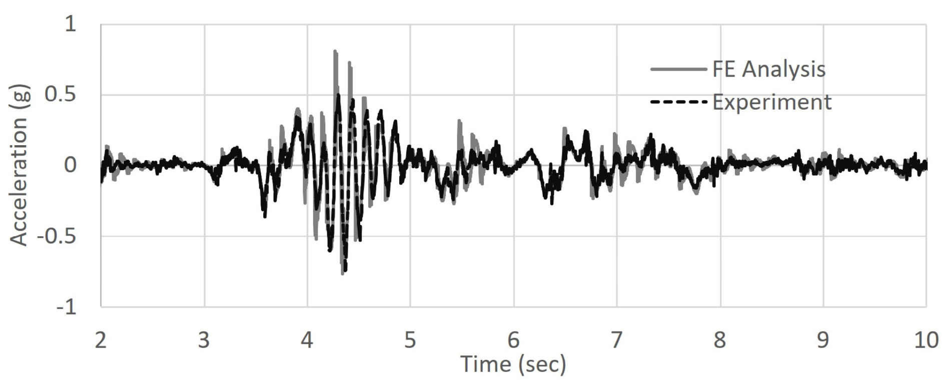


Figure 8. Comparison of acceleration time-history response

Figure 9 shows the comparison of responses of FE analysis employing the present modeling approach and the test results. It can be clearly seen that the reconciled modeling approach is able to reconcile test responses correctly. Moreover, this model is able to capture the correct frequency as well as the correct amplitude for the peak response. The FE analysis result shows a good comparison for all the responses at different values of frequencies. In addition to this, the modal analysis performed on this model also shows the rocking mode at the frequency value near 8.8 Hz. Thus, the comparison of the FE results and Test result employing the third modeling approach shows the effect of additional structures at the base of the cabinet on the dynamic responses.

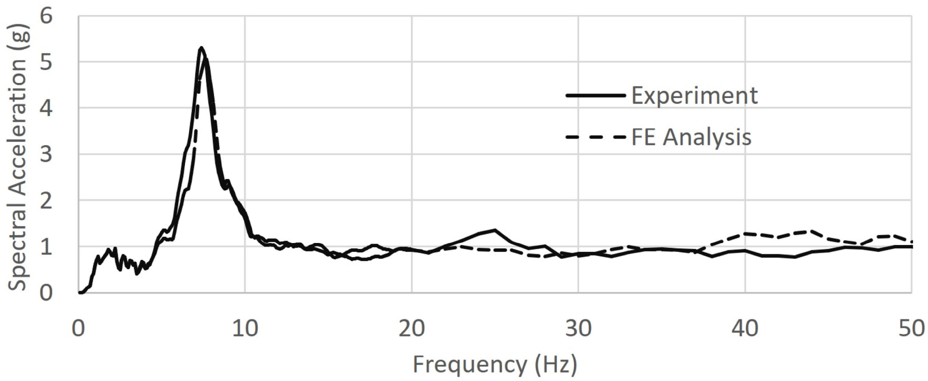
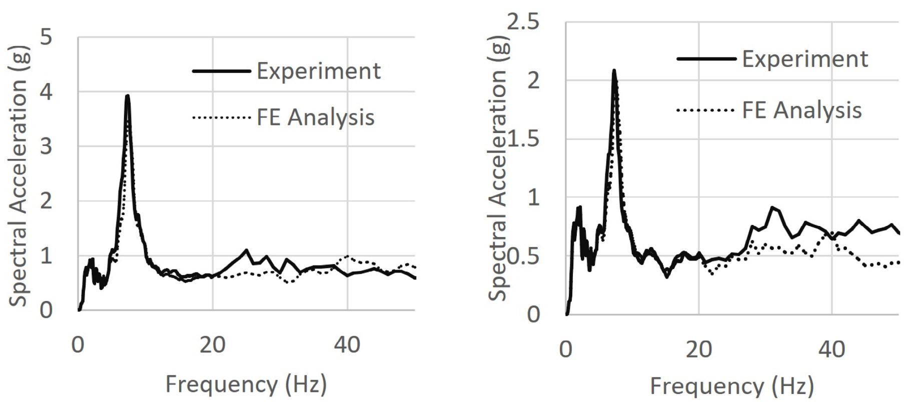


Figure 9. Response spectrum comparison at G1 accelerometer using reconciled modeling approach

The responses at different accelerometer locations are also compared for the third modeling approach. Each response at the designated locations shows a good fit with the actual test responses. Some of these comparisons are shown in the Figure 10 below.

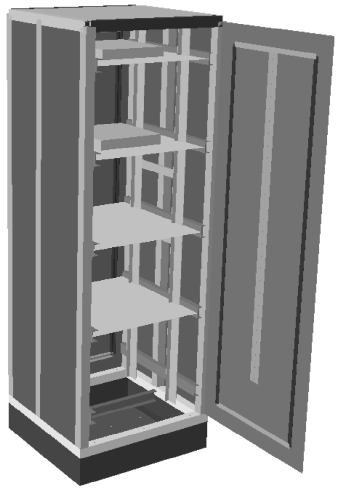


(a) Comparison at G2 Accelerometer (b) Comparison at G3 Accelerometer

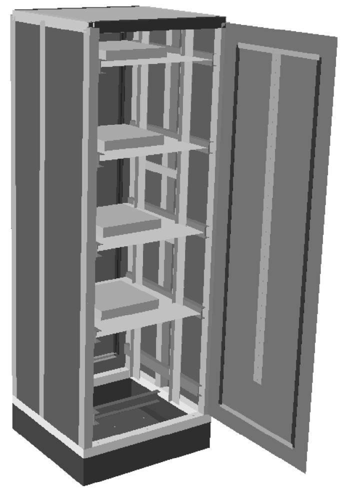
Figure 10. Response spectrum comparison at G2 and G3 accelerometers using approach 3

CABINET MODELING FOR OTHER CASES

As mentioned in Section 2 of this paper, the shake table experiment is performed for three different cabinet cases with different additional weights placed inside the cabinet. Section 3 of this report depicts the reconciliation of the test result for case 1, where no additional weight is placed inside the cabinet. Therefore, to reconcile the test result for the remaining two cases, the third FE modeling approach described in the Section 3 is employed by placing respective additional weights on the shelves of cabinet. To imitate the test scenario, the previously validated FE model is modified by placing two 50 kg weights on the top of the two shelves and the four 50 kg weights on the top of four shelves inside the cabinet for case 2 and case 3 respectively. The Figure 11a and Figure 11b show FE model of the cabinet with the additional weights corresponds to the case 2 and the case 3, respectively.



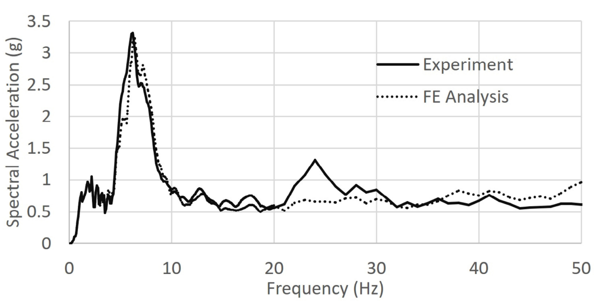
(a) Case 2: Two additional 50 Kg weights



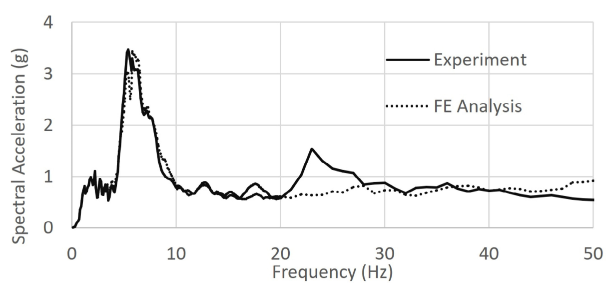
(b) Case 3: Four additional 50 Kg weights

Figure 11. Cabinet FE model for different cases

A nonlinear time history analysis is performed on the FE models for both case 2 and case 3 using the designated earthquake ground motion. The acceleration responses extracted at the G1 locations of the cabinet are used for the reconciliation of the test result with the respective FE analysis result. Figure 12 shows that the comparison of the test and FE result agrees well which increases the confidence in the response prediction capability of the FE model employing the third modeling approach.



(a) Comparison for Case 2 at G1



(b) Comparison for Case 3 at G1

Figure 12. Response spectrum comparison for Case 2 & 3 using approach 3

SUMMARY AND CONCLUSIONS

In this study, the effect of the mounting arrangement of an electrical cabinet on its seismic behavior is investigated. The FE software ABAQUS is used to model and perform the nonlinear time history analysis. Three different modeling approaches are used to explore the effect of additional mounting structures on the dynamic behavior of the cabinet. The acceleration time history responses are extracted at nodes corresponding to the designated location of the accelerometers and further used to generate the ICRS to compare with the experimental data. The difference in ICRS for all three approaches proves the argument that the additional mounting structures can make a huge difference in the dynamic behavior of the electrical cabinet. The key conclusions from this study are described below:

- The dynamic responses of the electrical cabinet are very sensitive to the cabinet base and mounting arrangement.
- The addition of a channel or channel with a base plate below the base of the cabinet makes a significant difference in the dynamic behavior of the cabinet as the addition of these two components induces considerable flexibility in the electrical cabinet.
- The test setup for the shake table tests needs to be consistent with the actual mounting conditions in the nuclear power plant.
- The shake table test, which has used additional mounting structures, is not correct for the qualification of the cabinet. Since the dynamic behavior of the cabinet used in the nuclear power plant will be different.

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