Seismic hazard studies conducted by nuclear power plants indicate that in Central and Eastern United States, the ground motion response spectra contain high-frequency amplitudes. High frequency spectral accelerations exceed the safe shutdown earthquake spectra considerably. Even though high-frequency ground motions do not cause damage to a structure, they can propagate through the structure and cause failure of acceleration-sensitive equipment such as relays. High frequencies interfere with the output of relays required to ensure safe shutdown of the plant during an earthquake. Hence, it is essential to determine the frequency content of motions that propagate through the structure, the electrical control panels and serve as input to the relays. The input motion to relays depends on the dynamic characteristics of the building and electrical control panels. This research is based on the hypothesis that high-frequency motion would not reach the equipment because of geometric nonlinearities that exist in the system. The displacements caused by high-frequency ground motions are relatively small. These small displacements would, therefore, be filtered out by the geometric nonlinearities such as gaps in a control panel’s mounting arrangement. This research explores the role of two different types of nonlinearities: (1) a gap in the connection between electrical control panel and floor; (2) sliding friction between control panel’s bolt and base plate. The results show that the high-frequency motion do not reach the relays if the maximum displacement of building floor is less than the gap. Even if the the displacement is larger than the gap, the inabinet spectral accelerations are not too high. On the contrary, results from a conventional linear analysis give excessively high unrealistic spectral accelerations.
Seismic Response of Electrical Equipment in Nuclear Power Plants

by
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To My Family and Friends
BIOGRAPHY

Sugandha Singh was born on January 23rd, 1991 in Haldwani, India. She grew up in the state of Uttarakhand, India. She joined the undergraduate program in Civil Engineering at College of Technology, G.B. Pant University of Agriculture & University, Pantnagar in July, 2008 and graduated with the Bachelors of Technology (B.Tech.) degree in May, 2012. Following graduation, she started working in Mumbai, India from July, 2012 at Shapoorji Pallonji & Co. Ltd. (Construction Materials Group) as a Project Engineer/Coordinator for two years. She joined North Carolina State University to pursue higher studies in August, 2014, where she received MS (2017) degree and is currently working towards obtaining PhD degree.

Sugandha’s research interests include structural dynamics and earthquake engineering with focus on the behavior of electrical cabinets and control panels. Sugandha is also a teaching assistant for the Structural Dynamics course at North Carolina State University.
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# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................ vii

LIST OF ABBREVIATIONS ........................................................................................... ix

**Part-I: Introduction** 1

1 Description of Problem ..............................................................................................1

2 Background ..................................................................................................................3

3 Proposed Study ...........................................................................................................4

4 Organization ...............................................................................................................5

**Part-II: Seismic Response of Electrical Equipment in Nuclear Power Plant** 6

1 Purpose .......................................................................................................................6

1.1 Background ..............................................................................................................6

1.2 Literature Review ...................................................................................................10

2 Seismic Behavior of Cabinets ..................................................................................13

2.1 Significance of Modes and Dynamic Characteristics of Cabinets ...................... 13

2.2 Significance of Mounting Arrangements ...............................................................16

3 Hypothesis ..................................................................................................................20

3.1 Cabinet Models ....................................................................................................21

3.1.1 Model-I- Gap Between Cabinet Anchorage & Floor .........................................21

3.1.2 Model-II- Friction Effects ..................................................................................23
4  Numerical Case Studies ................................................................. 24
5  Results ......................................................................................... 28
6  Conclusions .................................................................................. 51

**Part-III: Summary & Conclusions** 53

1  Summary ......................................................................................... 53
2  Conclusions .................................................................................... 54
3  Recommendations for Future Work ..................................................... 55
4  References ....................................................................................... 56
LIST OF FIGURES

1. Ground Motion Response Spectra for NPP site in CEUS 7
2. Ground Motion Response Spectra for Analysis 10
3. In-Cabinet Response Spectra for DGLSB-Frame 14
4. Mode Shape of DGLSB Cabinet-Door 15
5. Mode Shape of DGLSB Cabinet-Internal Frame 15
6. a. Cup-like Localized Deformation Around an Anchor Bolt 18
   b. Equivalent Model with Vertical Springs at Anchor Locations 18
7. Mounting Arrangement of a Cabinet 19
8. Model for Evaluating Resistance provided by Tubular Beams against Rigid Body Rotation 19
10. Force-Displacement Relationship of Gap Cabinet Model for Analysis 22
12. Schematic Representation of Numerical Case Study 27
13. Floor Response Spectra of Flexible Building ($\omega=3\text{Hz}$) 28
14. Floor Response Spectra of Rigid Building ($\omega=35\text{Hz}$) 29
15. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 1 and Case 2 30
16. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 3 & Case 4 31
17. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 5 & Case 6 32
18. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 7 33
19. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 8

20. ICRS for Nonlinear Base Case 1

21. ICRS for 5mm Gap Cabinet- Nonlinear Base Case 1

22. ICRS for Nonlinear Base Case 2

23. ICRS for 5mm Gap Cabinet-Nonlinear Base Case 2

24. ICRS for Nonlinear Base Case 3

25. FFT plot of Fixed-Base Cabinet for Case 3

26. FFT plot of 1mm Gap Cabinet for Case 3

27. FFT plot of 5mm Gap Cabinet for Case 3

28. ICRS for Nonlinear Base Case 4

29. ICRS for Nonlinear Base Case 5

30. ICRS for Nonlinear Base Case 6

31. ICRS for Nonlinear Base Case 7

32. ICRS for Nonlinear Base Case 8

33. ICRS for Nonlinear Base Case 8 (without Fixed-Base Cabinet)
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CEUS</strong></td>
<td>Central and Eastern United States</td>
</tr>
<tr>
<td><strong>EPRI</strong></td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td><strong>USNRC</strong></td>
<td>United States Nuclear Regulatory Commission</td>
</tr>
<tr>
<td><strong>NPP</strong></td>
<td>Nuclear Power Plants</td>
</tr>
<tr>
<td><strong>SSC</strong></td>
<td>Structure, Systems and Components</td>
</tr>
<tr>
<td><strong>LFEQ</strong></td>
<td>Low-Frequency Earthquake</td>
</tr>
<tr>
<td><strong>HFEQ</strong></td>
<td>High-Frequency Earthquake</td>
</tr>
<tr>
<td><strong>GMRS</strong></td>
<td>Ground Motion Response Spectra</td>
</tr>
<tr>
<td><strong>ISRS</strong></td>
<td>In-Structure Response Spectra</td>
</tr>
<tr>
<td><strong>ICRS</strong></td>
<td>In-Cabinet Response Spectra</td>
</tr>
<tr>
<td><strong>FFT</strong></td>
<td>Fast Fourier Transform</td>
</tr>
</tbody>
</table>
PART-I: INTRODUCTION

1 Description of Problem

In the wake of the devastation left behind by the earthquake and subsequent tsunami at the Fukushima Daiichi Nuclear power stations in 2011, the United States Nuclear Regulatory Commission (USNRC) appointed the Near-Term Task Force (NTTF). As part of Recommendation 2.1, the NTTF advised that all nuclear power plant (NPP) licensees should re-evaluate the possibility of external hazards in the plants and ensure that all structures, systems, and components of plants can withstand these external hazards. The hazard studies conducted in recent years indicate that for the majority of NPP sites in Central & Eastern United States (CEUS), the peak of ground motion response spectra (GMRS) is located in high-frequency region. The frequency content of GMRS is in the range 15-40 Hz whereas the frequency content of safe shutdown earthquake (SSE), which is the design basis for most plants, is 1-10Hz. As the majority of nuclear power plants are located in CEUS, the plants are currently in the process of evaluating vulnerability of their structures, systems, and components to high-frequency motions.

EPRI (2007), illustrates that the high-frequency motions do not cause damage to the power plant or heavy industrial structures and equipment. Analytically, it can be shown that the low frequency structures (flexible systems) do not exhibit significant amplifications due to the high-frequency input because the frequency ratio (ratio of the frequency of applied load to the natural
frequency of structure) is much greater than unity thereby resulting in a low value of dynamic amplification factor and hence, smaller response. On the other hand, structures with high natural frequency are too rigid to undergo large relative displacements and therefore do not exhibit excessive stresses due to small displacement amplitude of high-frequency ground motions. In addition to the structures and heavy industrial equipment, safe operation of a plant relies on electrical equipment such as relays which are acceleration-sensitive. The output signals from relays ensure safe shutdown of nuclear power plants during an earthquake. The earthquake motion that reaches relays and response of relays to these motions governs the relays’ output signal. The vulnerability of relays to high-frequency ground motion, however, has not been tested in prior studies for frequencies more than 16Hz (EPRI, 2015). Currently, the industry is amid establishing a testing program to determine the behavior of relays to high-frequency motion. Certain limitations in the process are:

- Traditional shake tables cannot operate at high frequencies. Thus, the cost of high-frequency testing is significantly high. Moreover, the appropriate facilities for such testing are scarce.
- Experts anticipate that the high magnitudes of high frequency accelerations are likely to render some of the currently used devices as unsafe. Consequently, the cost of appropriately qualified devices would increase.
- In some cases, structural modifications to electrical cabinets and control panels may be needed to reduce the magnitude of high-frequency motions.
- Solutions (related to the structural modifications) such as isolation pads and damping devices are costly and require periodic maintenance.
• The technology of semiconductor-based electro-mechanical devices is changing rapidly. As older devices become obsolete, research institutes, regulatory agencies and vendors/suppliers will have to continue spending resources on shake-table testing of newer devices.

2 Background

The earthquake input (i.e., cabinet acceleration) applied to the relays is altered by the building and cabinet before reaching the relays. The cabinet acceleration depends on the dynamic characteristics of the building and the cabinet. The in-cabinet response spectra (ICRS) is generated by using cabinet acceleration and it gives the frequency content of base motion by evaluating the maximum response of a series of single degree of freedom (SDOF) systems of different natural frequencies. Many studies (Gupta, Rustogi and Gupta et al., 1999; Yang, Rustogi and Gupta et al., 2002; Rustogi and Gupta et al., 2004; Herve et al., 2014) have been conducted to understand the seismic behavior of electrical cabinets in nuclear power plants and determine the factors that influence the in-cabinet response spectra.

Gupta, Rustogi, and Gupta et al. (1999) introduce a new method for evaluating in-cabinet response spectra by finding that response of a cabinet can be represented by only a few significant modes. A significant mode which governs ICRS can either be global cantilever mode of the cabinet or local mode of the door, internal frame or back wall depending on where the relay is mounted. Rayleigh-Ritz method is used to evaluate the mode shapes to represent the cabinet behavior. However, the significant global mode can occur due to rigid body rocking of cabinet in some cases. The rigid body rocking of cabinet is explored in greater detail by Yang, Rustogi & Gupta et al. (2002). They developed formulations to evaluate rocking stiffness depending on the mounting
arrangements of cabinets which facilitates incorporation of cabinet rocking mode in Ritz vector approach.

There are two types of geometric nonlinearities associated with cabinet rocking. First, when a cabinet is bolted and undergoes rocking, there exists a gap before the cabinet base comes in contact with the anchor bolt head. Thus, we hypothesize that the displacements caused by high-frequency ground motions can filter out because these displacements are relatively low. Herve et al. (2014) and Vlaski et al. (2013) study the nonlinearity in connection of the cabinet and the floor. Second is the nonlinearity caused by friction. The hole for the bolt at cabinet base plate is usually larger than the bolt diameter. Hence, when a ground motion acts at the cabinet base, initially the cabinet acts as fixed-base (linear-elastic) until the friction force resists the seismic force. When seismic force exceeds the friction force, the cabinet may slip from its position causing rigid body displacement of the cabinet.

Herve et al. (2014) discusses the propagation of high-frequency ground motions in the structure, mainly caused due to the impact of an aircraft. He proposes a nonlinear elastic system. The system has a 1mm gap in spring-mass-damper system. The study performed by Herve et al. (2014) forms the very basis of this thesis and is extended to study effects of different amounts of gaps in bolted connections (1mm, 5mm) subjected to both low-frequency as well as a high-frequency earthquake.

3 Proposed Study

Prior to an extensive testing program or hardware upgrades, it would be prudent to carefully evaluate the frequency content of earthquake motion that would reach the relays in a plant. In this research, we conduct a study to evaluate the frequency content of earthquake motion that would
reach relays. It is anticipated that high-frequency ground motion would filter out before they reach the relays due to various nonlinearities in the system such as gaps and friction. The specific steps taken to conduct this study are:

- Analyze the building subjected to ground motion for evaluating the floor motion where a cabinet might be located.
- Evaluate cabinet response due to floor-motion.
- Evaluate in-cabinet response spectra to determine the frequency content of motion reaching the relays.

The resulting in-cabinet response spectra would largely depend on the dynamic behavior of cabinet and building. The main factors that affect cabinet response are the structural configuration of cabinet and the mounting arrangement of the cabinet. In this study, we evaluate the effects of nonlinearities such as gaps and friction.

4 Organization

This thesis is divided primarily into 3 parts. Part-I gives the introduction and the objective of the proposed study along with some background information on existing literature pertinent to this study. Part-II of this thesis is a manuscript that will be submitted for possible publication as a journal article. This part of the thesis is an independent article that introduces the problem, discusses the existing literature briefly, and presents all the details of the research including in-depth discussion of results and conclusions. Finally, part-III of this thesis gives a summary and the conclusions of this research.
Part-II: Seismic Response of Electrical Equipment in Nuclear Power Plants

1 Purpose

1.1 Background

The design of nuclear power plants is required to comply with the United States Nuclear Regulatory Commission’s (USNRC) standard that probability of core melt should not be more than 1 in 10,000 years (USNRC, 2004; USNRC, 2012). A plant should be able to safely shutdown and maintain necessary operations to avoid core melt during and/or after an earthquake. The safety-related electrical equipment are critical for safe shutdown of plant and thus, are required to maintain their functionality.

Ground motion studies (SSHAC, 1997; EPRI, 2013) indicate that in Central & Eastern United States (CEUS) ground motions have high-frequency content due to the presence of hard rock soil profile as compared to low-frequency ground motion in the Western United States. However, the data recorded in CEUS is practically negligible to generate the design spectra for nuclear power plant sites. Hence, design spectra are typically generated from the data recorded in Western United States.

Following the damages caused by the earthquake and subsequent tsunami at Fukushima Daiichi nuclear power station in Japan, USNRC appointed a Near-Term Task Force (NTTF) to review the insights from Fukushima Daiichi accident and provide recommendations for enhancing
the safety of nuclear power plants in the USA (USNRC, 2011). NTTF’s Recommendation 2.1 requires the licensees to reevaluate the seismic and flooding hazards at their sites with respect to current USNRC requirements. Then, update the design basis and the structures, systems and components (SSCs) to safeguard against the updated hazards if necessary. At the same time, the results of Next Generation Attenuation-East (NGA-East) study indicate that ground motion response spectra (GMRS) in CEUS have high-frequency content (PEER, 2015). The frequency content of GMRS in CEUS ranges from 15-45Hz as compared to the frequency content of design safe shutdown earthquake (SSE) spectra which ranges from 1-10Hz. An example of the difference in response spectra at a site in CEUS is shown in Fig. 1. The seismic hazard studies along with NTTF recommendation required the NPPs to evaluate the vulnerability of their structure, system and components to high-frequency ground motions.

![Graph showing ground motion response spectra](image)

**Fig. 1.** Ground Motion Response Spectra for NPP site in CEUS (EPRI et al. 2015)

EPRI (2007), shows that the high-frequency ground motions do not cause damage to the power plant or heavy industrial structures and equipment. The structures with low natural frequency (flexible systems) do not get affected by the high-frequency input because the frequency
ratio (ratio of the frequency of applied load to the natural frequency of the system) is much more than unity resulting in a low value of dynamic amplification factor and hence, lower response. On the other hand, structures with high natural frequency are too rigid to undergo large relative displacements or excessive stresses due to small displacement amplitude of high-frequency ground motions.

Even though high-frequency ground motions do not affect the structure and heavy industry equipment, they may propagate through the structure and electrical cabinets to the safety-related electrical equipment such as relays. The output signal of relays is important for safe shutdown of the plant and may be influenced by high-frequency ground motions. Usually, relays are tested on shake tables before being used in NPPs (IEEE, 2013; EPRI, 2015). Historically, the relays have not been tested for ground motions with frequencies higher than 16Hz, the acceleration sensitivity of relays to such ground motions is unknown (EPRI, 2015). Electric Power Research Institute (EPRI) thus established a new testing program (EPRI, 2015) to test the vulnerability of relays when subjected to high-frequency ground motions.

In EPRI’s testing program, some relays and some other safety related equipment are subjected to high frequency ground motions with a wide range of frequencies that vary from 20 to 40Hz (EPRI, 2015). The capacity of the tested equipment for the high-frequency tests ranged mostly from 10g to 25g. The tests accounted for filtering of frequency as the ground motions propagate within the structure. However, the frequency content of ground motions may exceed 40Hz. Hence, the response of the relays which are subjected to ground motions with frequency content more than 40Hz is not known. Guidelines stated in EPRI (2015) help determine high-frequency consistent in-cabinet response spectra (ICRS) for safety evaluation of relays. The guidelines provided to determine ICRS are not site-specific and do not consider various nonlinear
factors such as soil-structure interaction, friction, gaps, etc. This would lead to conservatism in ICRS evaluation and may render many additional relays and other equipment to fail the safety assessments. Such conservatism increases the costs of operating the plant.

In this paper, we use simple systems to compare the ICRS obtained from the linear and nonlinear analyses. ICRS is generated from the total acceleration of cabinet, when a system consisting of building and cabinet is subjected to seismic excitation. The frequency content of this total cabinet acceleration time history affects the behavior of relays. Hence, the ICRS gives the frequency-content of ground motion experienced by the relays.

Two ground motions are used in the analysis. Since low-frequency ground motions are also likely to occur in various regions, the system is subjected to a low-frequency ground motion in addition to a high-frequency ground motion. The low-frequency ground motion used in the analysis is the TAFT earthquake (1952). TAFT earthquake has frequency content between 1-6 Hz and peak spectral acceleration occurs at 2.8Hz. The high-frequency ground motion used in the analysis is obtained from the design spectrum of a nuclear power station on the Eastern US. It has a frequency content in the range of 12-55Hz and peak spectral acceleration occurs at 35Hz. The ground motion response spectra for both motions are shown in Fig. 2. Both grounds motions are normalized to have peak ground acceleration of 1g.
1.2 Literature Review

EPRI (2007) focuses on analyzing the high-frequency ground motions and concludes that such motions are non-damaging to structures. EPRI (2007) evaluates base transfer functions for three different systems, the spring-mass-damper single degree of freedom system, the Timoshenko beam and the shear beam, to show that most structures are not affected by high-frequency ground motions. This study, however, does not discuss the response of electrical equipment to the high-frequency ground motions. The report also mentions various seismic events in the past in CEUS region where GMRS exceeded OBE and SSE in high-frequency content, and no significant damage to the structure was observed. However, Perry nuclear power plant, subjected to 1986 Northeastern Ohio Earthquake, which was undergoing operational testing at the time, experienced trips in some systems due to relay activation. Some fossil-fired power plants which were near Perry plant also experienced trips caused by turbine vibration sensors, etc. (USNRC, 1986, EPRI, 2007)
After the Near-Term Task Force (NTTF) had released its report (USNRC, 2011), USNRC issued a letter to all the licensees to follow the recommendations in the report and re-evaluate the safety of their plant structures, systems, and components. Since it is already established that the high-frequency ground motions only affect safety-related equipment, EPRI (2015) has established a high-frequency testing program to determine the vulnerability of relays and various other equipment critical for nuclear power plant safety. Some of the relays tested underwent chatter for low intensity but not at high frequency motions (EPRI, 2015). These guidelines help determine high-frequency consistent in-cabinet response spectra (ICRS) for safety evaluation of relays. The guidelines provided to determine ICRS are not site-specific or plant specific and do not consider various nonlinear factors such as soil-structure interaction, friction, gaps, etc. This would lead to excessive unwanted conservatism in ICRS evaluation and may render many additional relays not tested in the EPRI (2015) test program to fail safety assessments.

Many studies (Stafford 1975; Djordjevic & O’Sullivan et al., 1990; Djordjevic 1992; Gupta and Rustogi 1998; Gupta, Rustogi and Gupta et al., 1999; Yang et al., 2002; Rustogi & Gupta et al., 2004; Sankaranarayanan 2007; Cho, Kim & Chaudhary et al., 2011; Vlaski et al., 2013; Herve et al., 2014) have focused on understanding the seismic behavior of electrical cabinets and determine the factors that influence the in-cabinet response spectra. A summary of the main observations made in these studies is discussed below in order to understand the dynamic behavior of cabinets.

Gupta, Rustogi, and Gupta et al. (1999) introduces a new method for evaluating in-cabinet response spectra. In this method, the response of a cabinet is represented by only a few significant modes. A significant mode which governs ICRS can either be a global cantilever mode of the cabinet or a local mode of the door, internal frame or back wall depending on where the relay is
mounted. These mode shapes are calculated by Rayleigh-Ritz method to represent the cabinet behavior. However, for some cabinet, the significant global mode can also occur due to rigid body rocking of cabinet. The rigid body rocking of cabinet is explored in more detail by Yang, Rustogi & Gupta et al. (2002) and Makris & Zhang et al., 1999. They developed formulations to evaluate rocking stiffness for different mounting arrangements of cabinets which facilitates incorporation of cabinet rocking mode in Ritz vector approach. Rustogi and Gupta et al. (2004) used modal data obtained from shake table and in-situ tests of cabinets to validate finite element analysis as well as the basis for Ritz vector approach. Yang and Gupta et al. (2002) modify the originally proposed Ritz vector approach by incorporating cabinet rocking mode and account for partial rotational constraints provided by structural members of cabinets.

The studies mentioned in the previous paragraph do not discuss two important aspects associated with rocking behavior. First, when a cabinet is bolted and undergoes rocking, there is likely to be a gap between cabinet base and anchor bolt head. It is, thus, hypothesized that since the displacements caused by high-frequency ground motions are relatively small, these displacements can be filtered out due to the gap and consequently the high-frequency ground motion do not reach the relays. Herve et al. (2014) and Vlaski et al. (2013), discuss that high-frequency vibrations caused by an aircraft impact filter out before reaching equipment due to the presence of a small gap. Secondly, the hole for the bolt at cabinet base plate is usually larger than the bolt diameter. When a seismic motion acts at the cabinet base, the cabinet initially acts as fixed-base (linear-elastic) system until the friction force resists the seismic force. When seismic force exceeds the maximum friction force, the bolt may slip from its position causing rigid body linear displacement of the cabinet. This results in a nonlinearity due to friction. When the direction of
seismic motion is reversed, the cabinet again acts linear-elastically until seismic force exceeds the friction force.

Herve et al. (2014) studies the propagation of high-frequency ground motions in the structure, mainly caused due to an aircraft impact. Basing his work on the experimental findings of Vlaski et al. (2013), that high-frequency motions tend to filter out before reaching the equipment mounted in a cabinet, he also proposed a method to model and analyze a nonlinear elastic system. This system has a 1mm gap in spring-mass-damper system. The model proposed by Herve et al. (2014) forms the very basis of this research and is extended to study effects of different degree of gaps in bolted connections (1mm, 5mm) subjected to both low-frequency as well as high-frequency earthquakes. Herve et al. (2014), however, only defined the methods to evaluate floor response spectra and do not discuss the response of cabinet and relays.

2 Seismic Behavior of Electrical Cabinets

2.1 Significance of Modes & Dynamic Characteristics of Cabinets

Gupta, Rustogi & Gupta et al. (1999) show that only one or a few significant modes are sufficient to evaluate accurate ICRS. They compared ICRS obtained by analyzing the cabinets using all the modes and by using only one or two significant modes. Finite element modeling was used to analyze the cabinet and evaluate ICRS. As shown in Fig. 3, the in-cabinet response spectra obtained from both the analyses are almost identical. Using these results, they proposed mathematical functions and Rayleigh-Ritz method to represent cabinet behavior by a simple two degree of freedom system. The significant mode depends on various factors such as the location of relays, dynamic characteristics of a cabinet, etc.
The location of relays on the cabinet plays a significant role in evaluating the in-cabinet response spectra. Relays can be mounted on any component of the cabinet such as cabinet door, internal frame, back wall, etc. The frequency at which maximum amplification of in-cabinet response spectra occurs may or may not coincide with the fundamental frequency of the cabinet. For example, the peak of ICRS evaluated for an instrument mounted on the DGLSB cabinet door occurs at the fundamental frequency of cabinet. Implying that fundamental mode of the cabinet, which was also the local mode of the cabinet door, was the significant mode as well. On the other hand, the peak of ICRS for an instrument mounted on the internal frame of the same DGLSB cabinet did not coincide with the fundamental frequency of cabinet but coincided with the local modal frequency of the internal frame. Figs. 4 and 5 show the mode shapes of DGLSB cabinet door and internal frame, respectively.

Fig. 3. In-Cabinet Response Spectra for DGLSB- Frame (Gupta et al. 1999)
Fig. 4. Mode Shape of DGLSB Cabinet-Door (Gupta et al. 1999)

Fig. 5. Mode Shape of DGLSB Cabinet-Internal Frame (Gupta et al. 1999)

Various structural characteristics of the cabinet also affect its seismic behavior. The study conducted by Gupta, Rustogi & Gupta et al. (1999) highlights differences in the seismic behavior of different cabinets with different structural characteristics. For instance, in cabinet MS4706, no
non-rigid global mode occurred since the cabinet could not act as a free-standing cantilever, due
to high shear and torsional stiffness provided by steel side panels and top plate. Thus, the
significant mode of a relay mounted in this cabinet would be the local mode of either cabinet’s
door or internal frame, where the relay is mounted. Further, if a cabinet does not have rigid panels
on one or two side walls, the shear resistance from those walls is not offered thus resulting in
bending. Thus, the significant mode, in this case, can either be global cantilever mode due to
bending or superposition of global and local mode. These examples show the significance of
structural characteristics of cabinets in influencing their seismic behavior.

Although abovementioned work highlights some of the factors that impact the seismic behavior of
cabinets, they did not consider effects of different boundary conditions of the cabinet. Gupta &
Yang et al. (2002) have discussed this effect and formulate the rocking stiffness provided by
different types of mounting arrangements.

1.2 Significance of Mounting Arrangements

The importance of modeling the structural details of cabinet base to evaluate response
spectra was first shown by Llambias et al. (1989). He studied two electrical cabinets
experimentally as well as analytically to understand their seismic behavior and calculate in-
structure amplifications. At low amplitudes of excitation, both experimental and analytical results
predicted same natural frequencies and mode shapes. At higher amplitudes of excitation, however,
the seismic testing showed that the natural frequency of cabinet decreases with increase in the level
of excitation. The cabinets behave in a nonlinear manner since the first mode is a rigid body
rocking mode. He also observed that there are differences in the behavior of cabinets when it
rocked in either side-to-side or front-back direction. When rocking of the cabinets occurs in a side-
to-side direction, the stiffness decreased at higher excitation levels due to yielding of the gusset
plate and damping remained constant. On the other hand, if the cabinets rocks in front-back direction, the stiffness reduction is attributed mainly to yielding of plinth at the cabinet’s base.

Similarly, Lee et al. (1990) addressed the effects of in situ shimming at the cabinet base, on the seismic response. Their study shows that shim plates cause a discontinuity at the base of the cabinet. Thus, the stiffness of cabinets is less than that in shake table tests where the boundary condition is rather continuous. Moreover, Lee & Abou-Jaoude et al. (1992) study the effects of base uplift on cabinet response by modeling an SDOF system supported on a rigid beam which in turn is supported by two vertical compression springs. This study shows the importance of modeling base flexibility in determining dynamic characteristics of the cabinet.

Gupta et al. (1999) show that the global mode in the cabinet could either be just a rocking mode if the bending of cabinet is restricted due to resistance from side plates or it could be a combination of rocking and bending. In Ritz vector approach, appropriate mathematical functions are used to represent the global bending mode. The global rocking mode, however, cannot be considered without a knowledge of the rocking stiffness at the base of cabinet. Thus, Gupta & Yang et al. (2002) studied three types of widely used mounting arrangements for cabinets and developed formulations for calculating rocking stiffness imparted by these arrangements. The formulations are developed based on results of experimentally validated finite element models. The mounting arrangements of first two cabinets have a base plate fixed to the floor by anchor bolts and struts or rigid bars that are used as stiffeners. The anchor bolts restrict the rotation of cabinet’s base plate about the front edge. The base plate thus undergoes localized cup-like deformation as shown in Fig. 6(a) which is a region of high base plate curvature. The base plate curvature is negligible in the regions far from the anchor bolts and thus do not contribute to
rotational stiffness. Thus, the discrete springs at the location of anchor bolts represent the resistance provided by the anchor bolts in the analytical model shown in Fig. 6(b).

Another mounting arrangement, shown in Fig. 7, consists of only a triangular plate at each corner welded to the frame for bolting the arrangement to the floor. The frame is made of mainly two members; channel sections form the outer frame and intermediate tubular beams to provide continuity between the bays of cabinet. Hence, the localized cup-like deformation around anchor bolts on triangular plates similar to other two mounting configurations as well as the cantilever type bending of tubular beams provide the resistance to rigid body rotation of cabinet base. Fig. 8 shows the bending of tubular beams.

![Diagram](image_url)

**Fig. 6.** (a) Cup-like localized deformation around an anchor bolt; (b) Equivalent model with vertical springs at anchor locations (Gupta & Yang et al. 2002)
Rustogi & Gupta et al. (2004) compare results of in-situ and shake table tests on cabinets with the results of Ritz vector approach as originally proposed. The main differences between the tests and the analysis occur due to the presence of global rocking mode in experimental studies. Rocking occurs when the overturning moment due to inertial forces is more than the restoring forces of gravity about an edge.
3 Hypothesis

As discussed above in detail, the seismic behavior of a cabinet depends on the dynamic properties of the cabinet itself as well as the structural configuration of its mounting arrangement. Cabinets mounted with anchor bolts undergoes rigid body rocking which usually affects the fundamental mode of the cabinet. The rigid body rocking mode may be the significant mode in itself or may combine with a local mode. These factors affect the resulting in-cabinet response spectra and hence the frequency content of cabinet acceleration at the equipment level.

When a cabinet base is anchored to the floor and the cabinet undergoes rocking, there can be a gap between cabinet base plate and bolt head. Further, we have also discussed in section 1 that the displacement caused by high-frequency ground motions is relatively very less. We thus hypothesize that the high-frequency ground motion would filter out due to the existing gaps between the cabinet and the floor.

Nonlinearity may also occur due to friction that may exist at the cabinet base. This nonlinearity may occur because anchor bolt may exhibit some gap to allow cabinet sliding. Either, the hole for the bolt at cabinet base plate is a little larger than bolt diameter or the base plate may experience a tear around anchor bolt as has been observed experimentally. Hence, the cabinet acts as a fixed-base structure (linearly elastic) as long as the seismic force is less than the friction force. When the seismic force exceeds the friction force, the bolt may slip from its position causing a rigid body linear displacement of the cabinet resulting in a nonlinearity due to friction.

Hence, these nonlinearities can influence the propagation of the high-frequency seismic motions up to the relays. Thus, it can affect the response of cabinet and hence the in-cabinet response spectra.
3.1 **Cabinet Models**

In this study, we propose two models to represent the nonlinear seismic behavior of cabinets and understand their influence on the frequency content of motions that reach relays. The first model represents a gap that may exist between cabinet base plate and bolt head when a cabinet rocks. The second model represents the effect of sliding friction between the bolt and the base plate. A detailed discussion on these models is presented below.

3.1.1 **Model-I: Gap between Cabinet Anchorage & Floor**

This model signifies the gap in between the bolt head and the cabinet base plate as the cabinet rocks. Herve et al. (2014) considered a spring-mass-damper system with a gap of 1mm which is based on the recommendations by EPRI (2007) and International Atomic Energy Association (AIEA, 2012) as the cut-off displacement for the case of high-frequency motions due to an airplane impact. Fig. 9 shows the force-displacement relationship used in their study to represent this model which considers a gap of 1 mm in both the tension and compression.

![Fig. 9. Force-Displacement Relation for Nonlinear Elastic Response System proposed by Herve et al. (2014)](image-url)
Contrary to the recommendation by Herve et al. (2014), the gap associated with rocking behavior in a cabinet would exhibit zero force only in tension. The behavior in compression between the cabinet base plate and the floor is linear elastic with no gap. Furthermore, we consider two different magnitudes of gaps, 1 mm and 5 mm. Fig. 10 shows the force-displacement relationship of this model.

The force-displacement relationship shows that for displacement between 0mm and a predetermined gap, there is zero resisting static force in case of tension whereas for displacements more than the gap, the resisting static force follows linear elastic relationship. Hence, it is a nonlinear elastic model that exhibits geometric nonlinearity. The model follows a simple set of equations of motion which can be written as:

\[ m\ddot{u} + c\dot{u} = -m\ddot{u}_g, \quad 0 \leq u \leq u_{gap} \]  \hspace{1cm} (1)

\[ m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g, \quad u < 0 \]  \hspace{1cm} (2)

\[ m\ddot{u} + c\dot{u} + k(u - u_{gap}) = -m\ddot{u}_g, \quad 0 < u > u_{gap} \]  \hspace{1cm} (3)

Where, \( u_{gap} = 1\text{mm or 5mm} \)

Fig. 10. Force-Displacement Relationship of Gap Cabinet Model for Analysis
3.1.2 Model-II: Friction Effects

This model represents the effect of friction on seismic behavior of cabinets (Konstantinidis & Nikfar et al., 2015). As discussed earlier, the diameter of bolt hole in the base plate is often a little larger than the bolt diameter. Consequently, the friction forces would act at the interface of the bolt and the base plate. The cabinet would act as a linear elastic material when the seismic force is less than the friction force. When the seismic force becomes greater than the friction force, the cabinet would exhibit a slip in the direction of motion. As the direction of motion changes, the cabinet would again exhibit a linear elastic behavior until the time seismic force exceeds the friction force. Thus, the behavior is primarily hysteretic in nature and identical to that of an elastic-perfectly plastic material. Fig. 11 shows the force-displacement relationship for this model. The equations of motion for this model can be written as follows:

\[ m\ddot{u} + c\dot{u} + k_0 u = -m\ddot{u}_g, \quad |f| \leq f_y, k = k_0 \]  
\[ m\ddot{u} + c\dot{u} = -m\ddot{u}_g, \quad |f| \geq f_y, k = 0 \]  

When the direction of velocity changes,

\[ f(t + 1) = f(t) + \left(k_0(u(t + 1) - u(t))\right) \]  
\[ m\ddot{u}(t + 1) + c\dot{u}(t + 1) + f(t + 1) = -m\ddot{u}_g(t + 1) \]
In order to achieve the objective of this study, a numerical study is conducted by considering selective representative building-cabinet systems and earthquake ground motions. For simplicity and for facilitating appropriate interpretation of the phenomenon from the numerical data, both the building and the cabinet are represented by a respective SDOF system. The two ground motions considered in this study are same as those given in Fig. 2. Even though Fig. 2 shows spectrum curves normalized to a PGA of 1g, the actual motions used in the numerical study correspond to the actual PGA values for these motions. In case of low frequency ground motion represented by the Taft earthquake record, the PGA is equal to 0.159g and that for the high frequency ground motion is equal to 0.415g. At first, it may appear inappropriate to consider different PGA values for the two motions. However, the problem being studied is a nonlinear problem in which the behavior is highly dependent upon the degree of displacements. Therefore, the actual motions are used without any modifications. As noted in Fig 2, the peak of the spectrum curve for the low frequency Taft earthquake record occurs around 3 Hz and that for the high
frequency motion close to 35 Hz. Consequently, two different variations of the building and the cabinet are considered. A 3 Hz SDOF system is considered to represent a flexible building (or a flexible cabinet) and a 35 Hz SDOF system is considered to represent a rigid building (or a rigid cabinet). The damping ratio for the building is taken as 5% and that for the cabinet is taken as 2%. One may argue that the typical building frequencies are much less than 35 Hz. However, it must be noted that every building will have higher order modes in the frequency range of interest in this study. These modes will exhibit appreciable amplifications when subjected to a high frequency ground motion. Therefore, the high frequency systems are meant to be representative of higher order modes for both the buildings and the cabinets.

While the building model is linear-elastic in all cases, different nonlinear models are used to represent the cabinet. The specific nonlinear models considered in this study are described earlier in section 3.1. A total of four numerical cases are considered to represent different cabinets. One of these four cabinet cases correspond to the traditional/conventional case of linear-elastic or fixed-base model. In addition, two cases correspond to a gap nonlinearity. One considers a small gap of 1mm whereas the other a relatively larger gap of 5mm. Lastly, the fourth case corresponds to the elastic-perfectly plastic model representing the effect of friction between cabinet base plate and anchor bolts. Numerical integration with Newmark’s average acceleration is used for evaluating the floor motions and the in-cabinet motions. The floor motion is used as an input at the base of a cabinet for analysis (Katona et al., 1995). Relatively, a very small time step of integration equal to 0.0001s is used in this study in order to appropriately consider the effects of high frequency ground motions. Fig. 12 illustrates the various steps in the analysis of a single system. In summary, the various cases considered in this study can be enumerated as:

- Case-1: Flexible (3 Hz) building, flexible (3 Hz) cabinet, and low-frequency earthquake.
• Case-2: Same as Case-1 except that the ground motion is high-frequency earthquake.
• Case-3: Flexible (3 Hz) building, rigid (35 Hz) cabinet, and low-frequency earthquake.
• Case-4: Same as Case-3 except that the ground motion is high-frequency earthquake.
• Case-5: Rigid (35 Hz) building, flexible (3 Hz) cabinet, and low-frequency earthquake.
• Case-6: Same as Case-5 for high-frequency earthquake input.
• Case-7: Rigid (35 Hz) building, rigid (35 Hz) cabinet, and low-frequency earthquake.
• Case-8: Same as Case-7 for high-frequency earthquake.

For each of the above case, four different analysis are conducted corresponding to four different boundary conditions at the base of cabinet, i.e. fixed-base, gap of 1 mm, gap of 5 mm, and elastic-perfectly plastic.
\[ \omega = 3 \text{ or } 35 \text{Hz} \]
\[ \xi = 5\% \]

\[ M = 2000 \text{kg} \]
\[ \omega = 3 \text{ or } 35 \text{Hz} \]
\[ \xi = 2\% \]

\[ M = 100 \text{kg} \]
\[ \xi = 5\% \]

\[ \xi = 2\% \]

Fig. 12. Schematic Representation of Numerical Case Study
5 Results

In this section, we present the results of the analysis conducted for various cases described in the previous section. To begin with, the two types of building models, flexible building with natural frequency of 3Hz and rigid building with natural frequency of 35Hz are analyzed for both the low-frequency and the high-frequency ground motions. The in-structure response spectrum (ISRS) for a flexible building subjected to both the low and high frequency ground motions is shown in Fig. 13. As anticipated, the amplifications are much greater for the case of low frequency ground motion even though the PGA of low frequency ground motion is only 0.159g compared to 0.415g for high frequency ground motion.

![Floor Response Spectra of Flexible Building (ω=3Hz)](image)

**Fig. 13.** Floor Response Spectra of Flexible Building (ω=3Hz)
The floor response spectra for the case of a rigid building subjected to the two types of ground motions are compared in Fig. 14. As seen in this figure, the building truly behaves rigidly for the low frequency ground motion and there is no amplification as such. The floor spectrum is almost identical to the ground motion response spectrum (GMRS). However, the amplifications are significantly larger in the case of high frequency ground motion. The 35 Hz building which is conventionally considered to be rigid actually resonates with the input motion and does not behave rigidly.

![Figure 14. Floor Response Spectra of Rigid Building (ω=35Hz)](image)

*Fixed-Base Case-1 and Case-2:* Next, we consider a fixed-base linear-elastic cabinet and subject it to floor motions for various buildings. The resulting cabinet acceleration time histories are then used to generate the in-cabinet response spectra (ICRS). Fig. 15 compares the ICRS for Case-1 and Case-2. It also illustrates the relatively high spectral accelerations in ICRS compared to the
corresponding values in the in-structure response spectra (ISRS). The primary reason for high spectral accelerations is the tuning of the building frequency with the cabinet frequency.

Fig. 15. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 1 and Case 2

Fixed-Base Case-3 and Case-4: Fig. 16 compares the ICRS for these two cases of fixed base cabinets. As seen in this figure, the spectral accelerations in ICRS are relatively much less than those observed in Fig. 15. This observation is due to detuning of cabinet (rigid) and building frequencies. It can be seen that the spectral acceleration for the case of high frequency motions are relatively less than those for low frequency motion which is anticipated given that the building frequency is in resonance with the peak of low frequency GMRS.
**Fig. 16.** Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 3 & Case 4

**Fixed Base Case-5 and Case-6:** The various curves for ICRS and ISRS for these two cases of fixed base cabinets are compared in Fig. 17. As seen in this figure, the rigid building resonates with the high frequency ground motion leading to large values of spectral accelerations around 35 Hz in the ISRS. However, the spectral accelerations at 35 Hz in the corresponding ICRS are much less because the cabinet is quite flexible with respect to the high frequency ground motion and acts almost like an isolation system. It is interesting to note that spectral accelerations in ICRS are relatively high around 3 Hz which is the frequency of the flexible cabinets for both low and high frequency ground motions. While this observation is anticipated for the low frequency ground motion, the corresponding high spectral accelerations at 3 Hz for high frequency ground motion occur because the ground motion does not contain only high frequency content. It also contains some low amplitude low frequency input. These low amplitude pulses resonate with the flexible cabinet and therefore we observe amplifications in the ICRS in the vicinity of 3 Hz.
**Fig. 17.** Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 5 & Case 6

*Fixed Base Case-7 and Case-8:* This case is the most critical case of this study and forms of the very basis of conducting this study. The rigid building – rigid cabinet case is representative of a higher order building mode and higher order cabinet mode. The complete system is rigid and no amplification is observed between GMRS, ISRS, and ICRS when subjected to low frequency ground motion. This is shown in Fig. 18. However, when this system is subjected to a high frequency motion, the amplifications observed in ICRS are excessively large. Fig. 19 shows the corresponding spectra. As seen in this figure, the spectral accelerations at the peak of ICRS are almost unimaginable in real-life. Granted that this is only a simple system and that the amplifications illustrated in this example are much greater than what might be observed in a real-life system. Yet, it is theoretically possible to have such large amplifications in a real system with similar characteristics.
Fig. 18. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 7

Fig. 19. Comparison of Fixed-Base Cabinet ICRS with ISRS for Case 8
Even if the corresponding amplifications in the real-life cases are less than those observed in Fig. 19, the amplifications will be fairly high which can be explained as follows:

For a SDOF building with circular frequency $\omega_b$ and damping ratio $\xi_b$, subjected to a harmonic acceleration of frequency $\Omega$, we can write,

\[
\left( \frac{\ddot{u}_{f,max}^T}{\ddot{u}_{go}} \right) = TR_b = \frac{1 + (2\xi_b \beta_b)^2}{\sqrt{(1 - \beta_b^2)^2 + (2\xi_b \beta_b)^2}}
\]  

(8)

Where, $TR_b$ is the transmissibility ratio for the building and is defined as the ratio of floor acceleration amplitude to the amplitude of the ground motion acceleration. $\beta_b = \frac{\Omega}{\omega_b}$, is defined as the ratio of the frequency of the ground motion (or applied force) to the frequency of the building. $\ddot{u}_{f,max}^T$, is the amplitude of total floor acceleration and $\ddot{u}_{go}$, is the amplitude of ground motion acceleration.

For $\beta_b = 1$,

\[
TR_b \approx \frac{1}{2\xi_b}
\]

(9)

Next, let us calculate the amplification in SDOF cabinet of frequency $\omega_c$ and damping ratio $\xi_c$, subjected to a floor acceleration of magnitude $\ddot{u}_{f,max}^T$ at a frequency $\Omega$,

\[
\left( \frac{\ddot{u}_{c,max}^T}{\ddot{u}_{f,max}^T} \right) = TR_c = \frac{1 + (2\xi_c \beta_c)^2}{\sqrt{(1 - \beta_c^2)^2 + (2\xi_c \beta_c)^2}}
\]  

(10)

Where, $TR_c$ is the transmissibility ratio defined as the ratio of in-cabinet acceleration amplitude to that of the total floor acceleration amplitude. $\beta_c = \frac{\Omega}{\omega_c}$, is defined as the ratio of the frequency of
the floor acceleration to the frequency of the cabinet. $\ddot{u}_{c,max}^f$, is the amplitude of total cabinet acceleration.

For $\beta_c = 1$,

$$TR_c \approx \frac{1}{2\xi_c} \quad (11)$$

Finally, the in-cabinet motion is used as input for a SDOF system to calculate in-cabinet response spectra (ICRS). For an oscillator of frequency $\omega$ and damping ratio $\xi$, one can write the equation of motion as,

$$\ddot{x} + 2\xi\omega \dot{x} + \omega^2 x = -\ddot{u}_c^T \quad (12)$$

Thus, maximum displacement of the oscillator can be calculated as,

$$x_{max} = \frac{\left(\frac{\ddot{u}_{c,max}^T}{\omega^2}\right)}{\sqrt{(1 - \beta^2)^2 + (2\xi\beta)^2}} \quad (13)$$

Hence, for the response spectra,

$$S_D = x_{max}$$

$$S_A = \omega^2 S_D = \frac{\ddot{u}_{c,max}^T}{\sqrt{(1 - \beta^2)^2 + (2\xi\beta)^2}} \quad (14)$$

$$\Rightarrow$$

$$S_A = \frac{1}{\sqrt{(1 - \beta^2)^2 + (2\xi\beta)^2}} TR_c \ddot{u}_{f,max}^T$$

$$\Rightarrow$$

$$S_A = \frac{1}{\sqrt{(1 - \beta^2)^2 + (2\xi\beta)^2}} TR_c TR_b \ddot{u}_{go} \quad (15)$$
For $\beta = 1, \beta_c = 1, \beta_b = 1$,

$$S_A = \frac{1}{2\xi} * \frac{1}{2\xi_c} * \frac{1}{2\xi_b} \ddot{u}_{go}$$

For $\xi = 0.02, \xi_c = 0.02, \xi_b = 0.05$,

$$S_A = \frac{1}{2 * 0.02} * \frac{1}{2 * 0.02} * \frac{1}{2 * 0.05} \ddot{u}_{go}$$

$$\Rightarrow S_A = \frac{1}{0.04} * \frac{1}{0.04} * \frac{1}{0.10} \ddot{u}_{go}$$

$$\Rightarrow S_A = 6250 \ddot{u}_{go}$$ (16)

Hence, for a harmonic input with a PGA as small as 0.1g, i.e. $\ddot{u}_{go} = 0.1g$,

$$S_A = 6250 * 0.1g = 625g$$

The above discussion shows that it is theoretically possible to have excessively large values of ICRS if a linear elastic analysis is considered. For a ground motion with relatively small PGA of 0.1g, such large spectral accelerations are unrealistic in real-life applications.

Given the argument that arises based on the observations from Fig. 19, we explore the role of nonlinearity at cabinet mounting arrangement. Next, we present the results for ICRS as evaluated for the same systems but with different types of nonlinearities. These ICRS are compared with each other as well as to the corresponding ICRS for fixed base cases presented above.
**Nonlinear Base Case-1**: For this system, the building and cabinet are in resonance with the ground motion. Hence, there is a high amplitude of spectral acceleration at resonating frequency 3Hz for the linear elastic case. On the other hand, the amplitude of peak spectral acceleration for 1mm gap model is even higher than the fixed base linear elastic case because the maximum displacement of the floor is more than 1mm gap i.e., the maximum floor displacement is 6.14mm. When the cabinet base, in this case, hits the anchor bolt, an impulse is generated due to the high velocity of the cabinet which acts as an additional load. Repeated impulses thus resonate with natural frequency of cabinet and further adds to the already large response from linear analysis at the 3 Hz value. In contrast, the peak spectral acceleration is much less for the case of 5 mm gap as compared to the linear elastic model. Essentially, a 5mm gap filters out most of the displacement of the cabinet. Even though the maximum floor displacement (6.14 mm) is slightly larger than 5 mm, the floor

---

**Fig. 20.** ICRS for Nonlinear Base Case 1
motion for almost all the duration of this motion remains below 5 mm. Therefore, no amplification occurs due to linear-elastic response. Furthermore, this large floor displacement occurs only for a very short duration during the entire floor motion and the impulse caused by this large floor displacement does not add up to the linear-elastic response as the linear-elastic response is almost nonexistent. In addition to the gap boundary condition, Fig. 20 also gives ICRS for the case of elastic-perfectly plastic boundary condition (friction). As seen in the figure, the hysteresis loop dissipates some energy and therefore the peak of ICRS is less than that of fixed base case. The relatively low values of spectral accelerations in the ICRS for 5 mm gap case make it difficult to observe the true variation in Fig. 20. Therefore, Fig. 21 gives the ICRS for only the 5mm gap case. This figures can be used to make two observations. First, the peak spectral acceleration occurs at 1.7Hz instead of 3Hz. The frequency shifts because of reduction in stiffness of the cabinet, i.e. essentially zero stiffness when relative displacement of floor and cabinet is between zero and 5 mm gap. Second, an overall amplification can be seen in the peak spectral accelerations compared to GMRS. This observation is attributed to the maximum floor displacement being slightly greater than the gap.
**Fig. 21.** ICRS for 5mm Gap Cabinet- Nonlinear Base Case 1

*Nonlinear Base Case -2:* In this case, the ICRS are evaluated for same systems as in Figs. 20 and 21 but for a high frequency motion. The new ICRS curves are compared in Fig. 22. As discussed earlier, the high frequency ground motion also contains some low frequency content which resonates with the flexible building as well as flexible cabinet. Consequently, an amplification can be observed in the ICRS around 3 Hz for the case of fixed base linear-elastic analysis. The response is comparatively less for the elastic-perfectly plastic case due to energy dissipation by the hysteretic loop. ICRS generated by analyzing 1mm gap model also has a lower amplitude of peak spectral acceleration and peak cabinet acceleration than the fixed base linear-elastic cabinet but higher than elastic-perfectly plastic case. The response for 5mm gap case is relatively very less. For 1 mm gap case, the peak spectral acceleration is still quite high and around 10g. It is so because the maximum floor displacement is significantly large and equal to 11.25mm due to flexible nature.
of building and a much higher PGA of the high frequency ground motion. On the other hand, the response of 5mm gap models is relatively less because the gap filters out quite a bit of the floor displacement. For completeness, Fig. 23 shows the ICRS for only the 5mm gap case.

![Graph showing ICRS for Nonlinear Base Case 2]

**Fig. 22.** ICRS for Nonlinear Base Case 2
Fig. 23. ICRS for 5mm Gap Cabinet-Nonlinear Base Case 2

Nonlinear Base Case-3: Fig. 24 shows the ICRS of rigid cabinet mounted on flexible building subjected to low-frequency ground motion. In this case, since the cabinet is rigid, the linear elastic model has ICRS same as the ISRS at the floor. For elastic-perfectly plastic model, the ICRS is same as that of the fixed base linear elastic case but continues to have slightly higher amplitude before merging at peak cabinet acceleration which is same for both models. ICRS of models with gaps, on the other hand, show a very different trend. The trend is similar to linear elastic model until about 5Hz frequency and after that for 1mm gap cabinet, relatively higher amplitude of spectral acceleration can be observed. On the other hand, ICRS generated for 5mm gap case has smaller amplitude at low frequency and after 5Hz, there is a smooth curve.
This is a very peculiar observation and in order to understand it better, a fast fourier transform (FFT) is evaluated and compared for acceleration time histories of various cases. Figs. 25 – 27 give the FFT plots for the case of linear-elastic system, 1 mm gap case, and the 5 mm gap case, respectively. FFT for cabinet acceleration time history in the linear-elastic case shows that the primary frequencies contained in this motion occur between 1-5 Hz with maximum input at 3Hz. On the contrary, the FFT of 1mm gap shows that there are many frequencies from 3-100Hz contained in the in-cabinet acceleration time history which would resonate with different oscillator frequencies while generating response spectrum. This is because of the repeated impulses generated during this motion as the floor displacement is more than the gap. This impulse causes the cabinet to vibrate in its natural frequency under free vibration (35Hz) which then keeps altering because of repeated impulses. FFT plot for 5mm gap cabinet shows a very periodic pattern of

Fig. 24. ICRS for Nonlinear Base Case 3
frequency content of acceleration time history. Again, as explained for 1mm gap cabinet, the impulse is generated when cabinet base hits the bolt head and the cabinet then oscillates in its natural frequency until the next impulse. The maximum contribution to the response is from 3Hz frequency (as expected, since the cabinet is rigid and the ICRS should retrace floor response spectra in linear analysis and thus ICRS has main frequency content of 3Hz) and then impulse results in oscillations at high frequencies. From FFT plot, we can observe that there is a smooth curve-like envelop on higher frequencies, thus ICRS generated by using 5mm gap cabinet is a smooth curve.

Fig. 25. FFT plot of Fixed-Base Cabinet for Case 3
**Fig. 26.** FFT plot of 1mm Gap Cabinet for Case 3

**Fig. 27.** FFT plot of 5mm Gap Cabinet for Case 3
**Nonlinear Base Case-4:** Examining ICRS shown in Fig. 28 for a rigid cabinet mounted on flexible building subjected to high-frequency ground motion, we can note that linear-elastic and elastic-perfectly plastic cases have similar nature of response as that of previous case but with smaller amplitude. 1mm gap model has similar nature of ICRS (since maximum floor displacement in this case is 11.25mm) with slightly lesser amplitude than that of previous case. On the contrary, 5mm gap filters out most of the displacement and hence high-frequency ground motion. But the nature of ICRS seems to be similar to the previous case but with smaller amplitudes.

![Spectral Acceleration vs Frequency](image.png)

**Fig. 28. ICRS for Nonlinear Base Case 4**

In the previous cases, we observed that the natural frequency of building is also influencing the seismic behavior of cabinets.
**Nonlinear Base Case-5:** Fig. 29 shows ICRS of a flexible cabinet mounted on a rigid building subjected to low-frequency ground motion. In this case, the building is too rigid to be affected by low-frequency ground motion and hence, the relative displacement will be negligible and the ISRS will be same as GMRS. Due to this, the main frequency of total floor acceleration is 3Hz (input ground motion) which resonates with cabinet frequency resulting in the high amplitude of peak spectral acceleration of ICRS. Since the maximum floor displacement (6.01mm), in this case, is higher than that of gaps 1mm and 5mm, peak spectral acceleration and peak cabinet acceleration in ICRS for gap models is also more than that of ISRS. However, it can be noticed that the frequency of peak spectral acceleration for ICRS of 1mm gap cabinet occurs at around 2.10Hz instead of 3Hz (which is the frequency content ISRS) and that of 5mm gap cabinet occurs at even lower frequency of around 1.7Hz as observed earlier in Fig. 21 as well. The elastic-perfectly plastic model initially behaves as a linear-elastic model until seismic forces are more than friction forces which leads to hysteretic behavior. Thus, the trend of ICRS is similar but the peak spectral acceleration is slightly smaller than the linear-elastic model.
Nonlinear Base Case 6: A high-frequency ground motion is applied at the base of the system discussed above and Fig. 30 shows the ICRS for this case. The building’s natural frequency, when subjected to high-frequency ground motion, resonates with ground motion’s frequency at 35 Hz and thus peak spectral acceleration occurs at 35 Hz. But the cabinet is flexible with the natural frequency of 3 Hz. Thus, the response of the linear-elastic cabinet is less as compared to ISRS with peak cabinet acceleration of only 0.4 g. Similar to all other cases, elastic-perfectly plastic model has the same trend as that of the linear-elastic model with somewhat smaller amplitudes of peak spectral acceleration and peak cabinet acceleration. Moreover, both the gap models are filtering out the displacement and high-frequency of ground motion. Thus, ICRS of both gap models have very less peak spectral accelerations and even lesser peak cabinet acceleration at around 0.23 g for 5 mm gap cabinet and 0.29 g for 1 mm gap cabinet.
Fig. 30. ICRS for Nonlinear Base Case 6

Nonlinear Base Case-7: Fig. 31 shows ICRS of a system with rigid cabinet mounted on rigid building subjected to low-frequency ground motion. Since ISRS is same as GMRS, the frequency content of total floor acceleration remains 3Hz, and hence the cabinet is too rigid for this case. Thus, ICRS for linear-elastic as well as elastic-perfectly plastic models are similar to ISRS with slightly higher amplitudes. On the other hand, the maximum displacement of the floor (6.01mm) is more than that of the gap and hence ICRS of gap models have higher amplitudes. The nature of ICRS for gap cabinets is same as that ICRS shown in Fig. 24.
Nonlinear Base Case 8: Finally, the high-frequency ground motion is applied at the base of the system discussed above, and Fig. 32 shows ICRS. The natural frequency of linear-elastic model resonates with the frequency content of input floor acceleration and hence, the peak spectral acceleration of ICRS of linear elastic cabinet is very high as compared to all other models and ISRS. It should be noted here that only because the system is perfectly in resonance with the ground motion, the peak spectral acceleration is very high, otherwise it is not practical for this high amplitude to occur. This is precisely the problem being faced by the plants in Central and Eastern US currently. Theoretically, a linear-elastic analysis results in acceleration levels that are unrealistic and not observed in typical earthquakes even when the earthquakes have had high frequency content. This case is the primary motivation behind this thesis.
Fig. 32. ICRS for Nonlinear Base Case 8

Fig. 33 shows the ICRS of all the other cabinet models as it their variation is difficult to observe in Fig. 32. The nature of ICRS in elastic-perfectly plastic cabinet is similar to that of linear-elastic cabinet but with significantly smaller peak spectral acceleration as well as peak cabinet acceleration. On the other hand, the maximum floor displacement (11.18mm) is more than the gap. Therefore, the ICRS for both gap models is observed to be similar to that in previous cases. The amplitude is smaller for 5mm gap cabinet as compared to the previous case.
In summary, the primary observations and conclusions drawn from the results presented above are:

- A linear-elastic analysis can result in excessively high (unrealistic) spectral accelerations in the case of a rigid building and rigid cabinet subjected to high frequency ground motion. Currently, the plants are faced with precisely this situation as every building and every cabinet has a high frequency mode that is close to or in perfect tuning with each other and with the frequency of input motion. However, as illustrated in this study, it is a theoretical situation and even a very small degree of nonlinearity reduces such high unrealistic accelerations to more realistic values. If the results of a linear-elastic analysis are used in seismic qualification of relays or other electrical instruments, then most of the instruments...
are likely to fail the qualification and the cost of operating and upgrading the plant will be unrealistic too.

- The peak spectral acceleration and peak cabinet acceleration in ICRS for nonlinear cases of gap models depend on the maximum floor displacement. If the maximum floor displacement is less than the gap, the ICRS is observed to be significantly less, i.e. they filter out the motion as hypothesized at the beginning of this study.

- If floor displacement is greater than the gap, then ICRS has a relatively larger amplitude in the high-frequency range in the case of rigid cabinets and higher amplitudes in the low-frequency range for flexible cabinets. However, the amplitude values are of similar order as observed in existing designs. In such cases, there exist possibility of repeated impulses which can result in high frequency oscillations. The relays and other instruments must be qualified for such motions which are a reality in actual plants due to the existence of such nonlinearities in real-life.

- ICRS calculated by analyzing cabinet with elastic-perfectly plastic model follows a trend similar to that of the fixed-base cabinet but with somewhat smaller amplitudes mainly due to energy dissipation in the hysteretic loop.
Part-III: Summary & Conclusions

1 Summary

The functionality of safety-related equipment is critical in maintaining safe operation of nuclear power plants during and after the earthquake. The equipment response depends on the dynamic characteristics of the building and the electrical cabinets. Currently, the in-cabinet response spectra (ICRS) is evaluated by analyzing a fixed-base cabinet model. These fixed-base models give excessively conservative results particularly for high frequency earthquake ground motions. The extremely high spectral accelerations in such cases are essentially unrealistic. In this study, ICRS are obtained by analysis of fixed-base model as well as the nonlinear cabinet models. Two types of cabinet models are used to represent nonlinear behavior of the cabinet: 1) Nonlinearity due to gap which may be observed during rigid-body rocking of the cabinet; 2) Nonlinearity due to friction exhibited due to the sliding of the cabinet. For the case of gap, two different conditions are considered. One with a very small 1mm gap and the other with a 5mm gap. A comparison of results from different types of cabinet models shows the importance of considering realistic mounting conditions in the evaluation of ICRS. The primary observations and conclusions of this study are summarized below.
2 Conclusions

The following conclusions are made from the observations made in this study:

- The response spectra obtained from nonlinear cabinet models have significantly less amplitudes as compared to the linear-elastic cabinet model. In majority of the cases, the amplitude of spectral accelerations in linear-elastic model are unrealistically high. This is a key issue faced currently by the nuclear industry. Tuning of building and cabinet modes with each other and with the ground motions results in very high amplitudes of acceleration. These amplifications are only theoretical in nature and if relay qualification studies would consider these amplifications, the relays would fail to qualify leading to increased cost.

- On the contrary, the nonlinear cabinet models show that the amplitude of the spectral accelerations are comparatively low and more realistic. In the ICRS obtained from analysis of gap models, the ground motion is filtered out due to the gap. On the other hand, in the ICRS obtained from elastic-perfectly plastic cabinet model, lower amplitudes can be attributed to the energy dissipated in the hysteresis loop. In most cases, the amplitude of peak spectral accelerations is well below the amplitudes at which the relays have been observed to fail during shake table testing.

- Furthermore, the amplitudes of spectral accelerations in gap cabinet models depend on the floor displacement. If the floor displacement is less than the gap, the amplitudes of ICRS are significantly less. However, if the floor displacement is more than the gap, the amplitude of ICRS are relatively higher in the high-frequency region for the rigid cabinets and in the low-frequency region for the flexible cabinets. This is due to periodic impacts in the cabinet base leading to an increase in the relative displacement.
of the cabinet. The relays and other equipment mounted on cabinet must be qualified for such motions which are a reality in actual plants due to the existence of such nonlinearities in real-life.

In flexible cabinet models with gap, in some of the cases, the peak spectral accelerations are observed to occur at frequencies lesser than the natural frequency of the cabinet. This indicates that the stiffness of the cabinet is reduced due to the presence of the gap. This result emphasizes the significance of appropriately modeling the mounting arrangement. The observations made from the results clearly indicate that equipment response differs for different cabinet models. The geometric nonlinearities considered in this research exist in real-life building-cabinet system and thus affect the amplitudes of spectral accelerations and nature of ICRS. The stiffness of the cabinet varies depending on the connection of cabinet base and the floor. Thus, the nonlinearities as mentioned in this study should be realistically modeled in the analysis to qualify the relays in order to obtain better estimates of the response of the relays.

3 Recommendations for Future Work

There are several aspects that need to be explored further in this area of research to facilitate accurate evaluation of ICRS. Some of these are:

- Consider MDOF system building and MDOF system cabinet models.
- Analyze real-life cabinet with the contact elements at the base of the cabinets representing gap and sliding friction and comparison with experimental tests.
- Consider coupled building-cabinet systems and observe the difference in results due to non-classical damping, mass interaction, etc.
4 References


