TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Mô hình số cho tủ điện trong nhà máy điện hạt nhân: tổng quan

Trần Thanh Tuấn[1,*], Nguyễn Phú Cường[2], Dookie Kim[3,*]

[1]Viện năng lượng gió ngoài khơi, Trường Đại học Quốc gia Kunsan, tỉnh Jeollabuk, Hàn Quốc
[2]Nhóm nghiên cứu kỹ thuật kết cấu nâng cao, Bộ môn Công trình, Trường Đại học Mở Thành phố Hồ Chí Minh, Thành phố Hồ Chí Minh, Việt Nam
[3]Khoa Xây dựng và môi trường, Trường Đại học Quốc gia Kongju, Hàn Quốc

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TÓM TẮT

Xây dựng mô hình số cho tủ điện trong nhà máy điện hạt nhân đóng vai trò quan trọng trong việc đánh giá rủi ro động đất. Mô hình phần tử hữu hạn cho phân tích phi tuyến thường tốn nhiều thời gian do sự phức tạp của nó. Trong khi đó, mô hình đơn giản hóa có thể giảm thiểu đáng kể sự phức tạp, tuy nhiên các đặc điểm động lực học (khối lượng, dạng dao động, hay ứng xử phi tuyến) thường không được đánh giá đầy đủ. Bài báo này trình bày tổng quan cách tiếp cận hiện tại trong việc xây dựng mô hình cho các tủ điện. Kết quả nghiên cứu đóng vai trò là

**Tác giả liên hệ chính.*
Email: tranthanhtuan@kunsan.ac.kr, kim2kie@kongju.ac.kr

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Finite element modelling of electric cabinets in nuclear power plants: a review

Thanh-Tuan Tran[1,*], Phu-Cuong Nguyen[2], Dookie Kim[3,*]

[1]*Institute of Offshore Wind Energy, Kunsan National University, Jeollabuk-do, Republic of Korea*
[2]*Advanced Structural Engineering Laboratory, Department of Structural Engineering, Ho Chi Minh City Open University, Ho Chi Minh City, Vietnam*
[3]*Department of Civil and Environmental Engineering, Kongju National University, Republic of Korea*

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ABSTRACT

The development of numerical modeling for safety-related cabinet facilities plays an essential role in seismic risk assessment. For nonlinear time history analysis, a full finite element model is often time-consuming due to its computational complexity. A simplified model can significantly reduce modeling complexity, however, the dynamic characteristics (such as mass, local mode shapes, or nonlinear behavior) are not fully captured. The current paper presents an overview of the current literature addressing the development of cabinet modeling. The results are expected to serve as a general reference and starting point to new researchers.

Keywords: *Cabinet facility, nuclear power plant, simplified model, finite element modeling.*

1. INTRODUCTION

Electric cabinet is one of the essential facilities in nuclear power plants (NPPs). This equipment is sensitive to acceleration due to carrying relays and switches.[1] During an earthquake, the cabinets can be damaged and they can extend the accident to nearby structures triggering an uncontrolled mechanism known as the Domino Effect (see Figure 1).[2] Besides, the cabinet contains many power distribution systems such as electric switchboard, control transformer, or control circuit fuse, and so on, which is quite sensitive to the performance of the cabinet. The damage to the mechanical and electrical equipment in nuclear power plants causes the large social and economic damage. Therefore, the seismic performance of these non-structural components should be considered carefully.[3-11]

Generally, to assess the structural performance of cabinet facilities, the experiment and finite element methods are popularly used.[12-14] However, these approaches are expensive and the result interpretation may be difficult. As shown in Figure 2, the experimental approach is the most time-consuming compared to the analytical one, and when the equipment complexity increases, the analysis time increases.[15] The large portion of experimental works leads to the cost increase. Additionally, it is noted that finite element analysis can produce serious errors due to inexperience on the part of users.[16] Moreover, due to the complexity of the attached electrical devices, it will take a long time for analysis.

**Corresponding author.*
Email: tranthanhtuan@kunsan.ac.kr, kim2kie@kongju.ac.kr

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Figure 1. Damage of non-structural components.[19]

to overcome the above limitation, there is a need to develop a simplified approach for practical reasons. In 2016, Lim[18] developed a method for generating simplified finite element models for electrical cabinets, which can capture the buckling behavior or failure of connectors of cabinet structure. Various researchers developed numerical models of cabinets that can capture the buckling of steel plates, failure of connectors, and the local buckling effect and nonlinear behavior support boundary conditions.[16-19]

The present paper focuses on surveying the reported numerical modeling for cabinet facilities in the nuclear industry. Firstly, the important structural features of electrical cabinets are described in Section 2. Secondly, numerical modeling of the electric cabinet using Finite Element Model (FEM) is given in Section 3. Finally, the methodology for generating the numerical modeling of the electric cabinet using the simplified approach is discussed in Section 4.

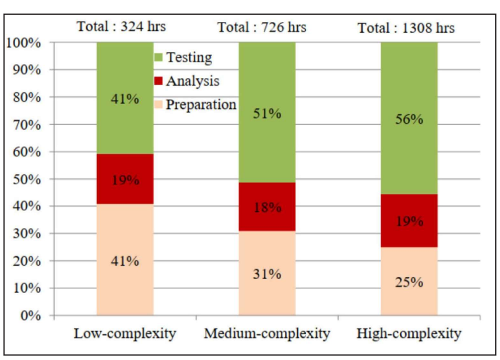

Figure 2. Work content and hours estimation for nonstructural qualification based on the complexity of the electrical equipment.[15]

2. IMPORTANT STRUCTURAL FEATURES OF ELECTRICAL CABINETS

Framing members, steel plates, and the connections between framing members and plates/framing members are the main components of a cabinet. The framing members are usually connected to each other using fasteners (i.e., weld, screw, or bolt). The enclosure steel panels are usually connected to the framing members via screw or bolt fasteners. The base-frame members of the cabinet structure are then anchored to the floor through channel-section frames using bolt connectors (Figure 3).[21]

In a cabinet structure, the frame members work similarly to the framing elements of a steel frame. During seismic loadings, the collapse of an electrical cabinet causes the following reasons: (i) failure of connections at the base or between plates with frame members, (ii) buckling of the plates, and (iii) buckling of the frame members.

Other components including operational, bracing, and isolation systems may contribute to the dynamic performance of the cabinet.[15] Operational attachments are any parts attached to the cabinet to maintain its active operation (Figure 4). The bracing attachments can improve the structural rigidity and reduce relative displacements of the cabinets. And the isolation reduces seismic demand and dynamic amplification in cabinets as well as modifying their dynamic characteristics.

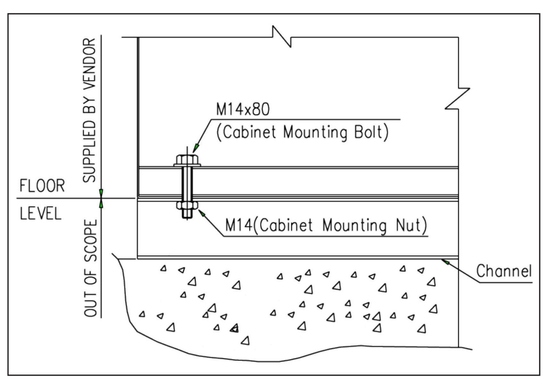

Figure 3. Details of anchor bolt.[20]

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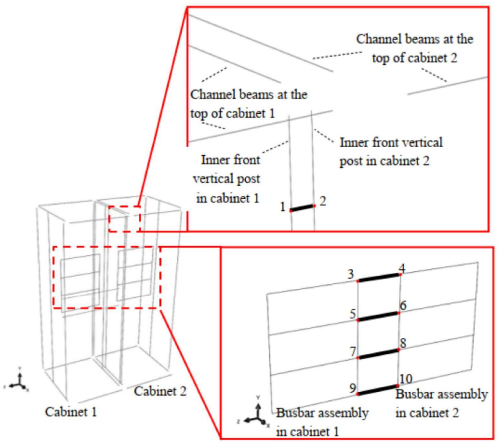
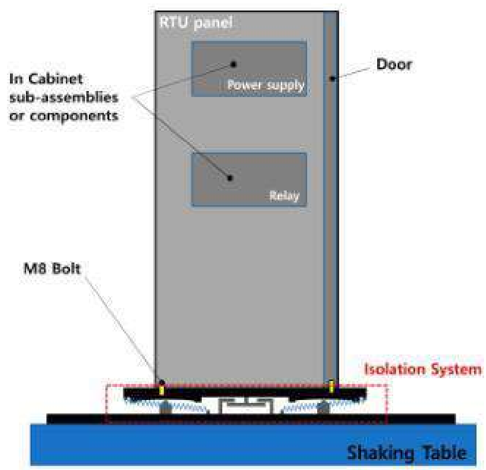
(a) Electrical conduilt [18]



(b) Additonal bracing system [18]



(c) Isolation system [20]

Figure 4. Components in the cabinet.

3. FULL FINITE ELEMENT MODELS

As empirical data has numerous limitations and large numbers of specimens cannot be tested on shake tables, it is more practical to evaluate the seismic vulnerability of electrical equipment using numerical techniques, such as finite element. Using Finite Element Model with the supports of finite element softwares is easy to capture the dynamic behavior of the cabinet under various boundary conditions and loading configurations.

In 1999, Gupta *et al*.[22] developed finite element models of 16 types of electric cabinets. One of them is the DGLSB cabinet (Figure 5) which is an individual unit and instrument mount on the doors and internal frame. This FE model were verified with the results reported by Rustogi and Gupta.[23] The outcomes from the analysis are used to evaluate in-cabinet response spectra needed in the seismic qualification of electric instruments.[24-25] Later, the method was modified by Gupta and Yang[26] to overcome limitations that were encountered during applications to actual cabinets. The results show that the contribution mode, called "significant mode", is a local mode of the cabinet in most cases. However, in some cases, the global cantilever mode of the cabinet may also be significant along with or without the local modes.

Likely, the FEM of the cabinet is generated using SAP2000 by Tran *et al*.,[27–29] as shown in Figure 6. The main-frames and sub-frames are modeled using the frame elements, and the steel plates are modeled using the shell elements. Plates and frames are connected by link elements. The connection between the door and main-frame is simulated as a hinge, which is fixed at five degrees of freedom. Meanwhile, the locks between panels and main-frames are fixed at three translational degrees of freedom. For the support boundary condition, the simplified pressure-cone method as stated by Shigley is adopted to calculate the stiffness of the anchor bolt.[30] Later, using this developed FEM, Cao *et al.*[31] proposed a simplified approach for assessing the seismic risks for cabinets. The method is a combination of fragility analysis and cumulative absolute velocity (CAV) analysis.

In reality, the cabinets will be connected together and how rational is the approach to consider the seismic response of a single electrical cabinet and its integration into the multi-cabinets (as called a "grouping effects") (Figure 7).[32–34] The grouping effect is the inclusion of the structural modification to the idea and it was considered in the form of two entities mainly the mass and stiffness provided by the cabinets. The rigid links are considered for connecting the cabinets, which is not inducing any change in the dynamic characteristic of the structure.

Regarding the impact of boundary conditions on the performance of electric cabinets, various researches are also studied. Rocking behavior of cabinet subjected to Reg. 1.60[35] was carried out by Jeon *et al.*[36] In this research, different models were developed using Abaqus and ANSYS, and verified using the experiment data.

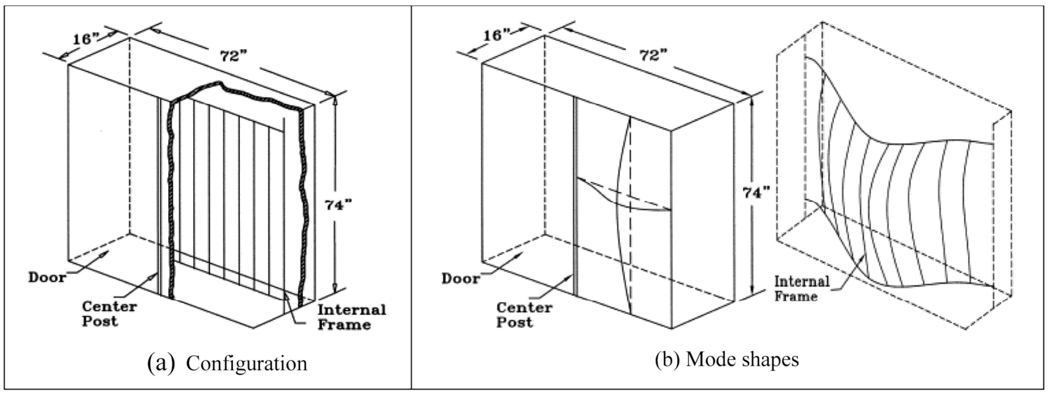


Figure 5. Cabinet models proposed, adapted from Gupta *et al.*[22]

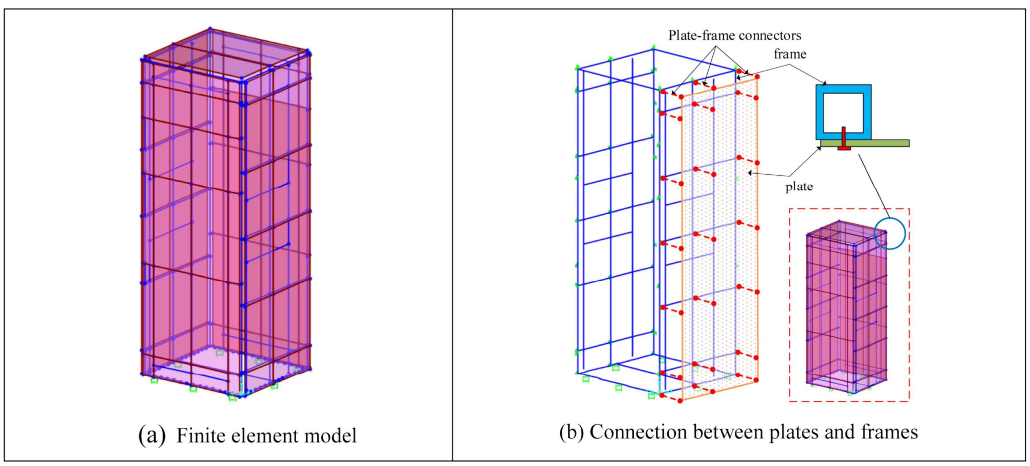


Figure 6. Cabinet models proposed, adapted from Tran *et al.*[27]

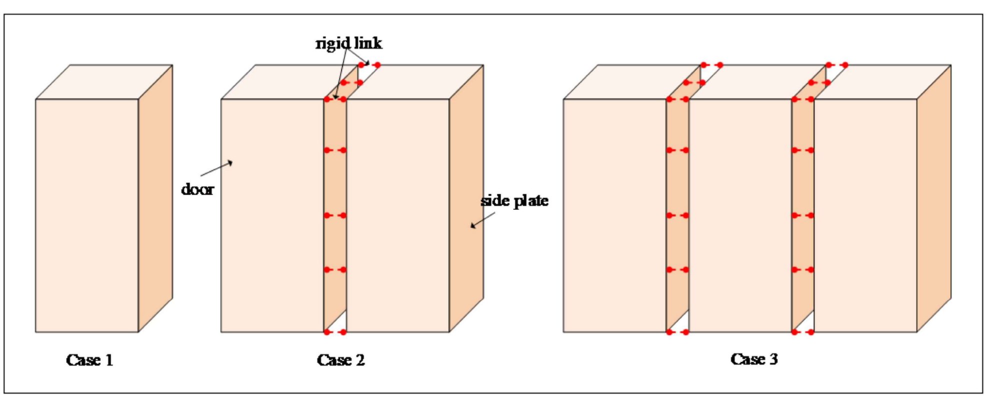


Figure 7. Typical cabinet models, adapted from Salman *et al.* [32,33]

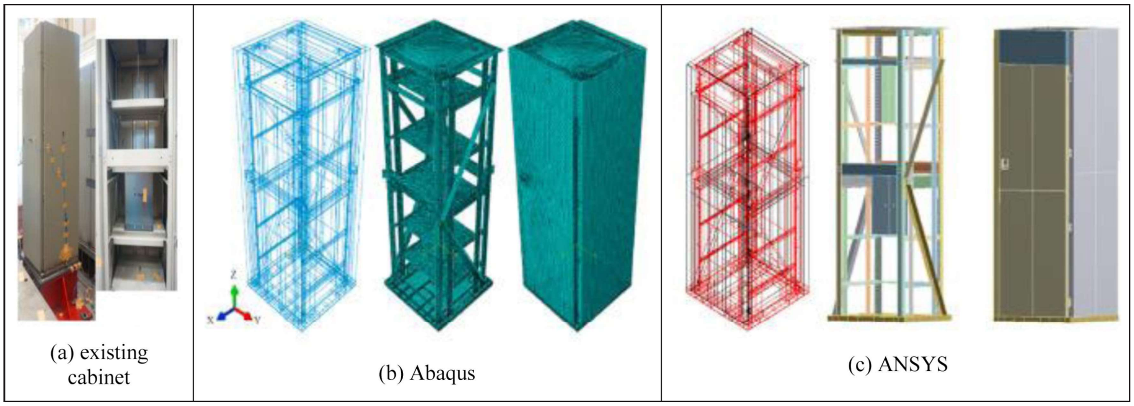


Figure 8. Finite element models of cabinet, adapted from Jeon *et al*. [36]

4. SIMPLIFIED FINITE ELEMENT MODELS

In 2016, Lim[18] developed a method to generate simplified finite element models for electrical cabinets. The model is comprised of beam elements, shell elements, and spring and constraint equations. These models can capture the nonlinear behavior of cabinet structure, such as the buckling of steel plates, failure of connectors, and the local buckling effect near the end of the framing members. In this research, two configurations of cabinet namely Class I and Class II are presented, as shown in Figure 9. Class I is a model of an electrical switchboard cabinet where all structural components are constructed from plain sections. Class II is the model with some applied improvements of the screw connections between plates and framing members. A comparison of the modeling features between Class I and Class II is summarized in Table 1. Besides, the effects of electric devices installed inside the cabinet (i.e., busbar, main circuit breaker, and meter devices) on the nonstructural performance were also studied.

Later, Tran *et al*.[37] also developed bare-frame model to capture the local buckling behavior of frame members. The numerical models are developed using OpenSees.[38] The fiber-based plasticity approach, which can capture the nonlinear behavior, is utilized. In this model, the elements must be discretized into fibers, as shown in Figure 10. Five integration points divide elements into sub-elements. To consider the nonlinear behavior, the relationship of stress-strain of each fiber on the cross-section of the sub-element (i.e., steel01, steel02) is defined.[39-41]

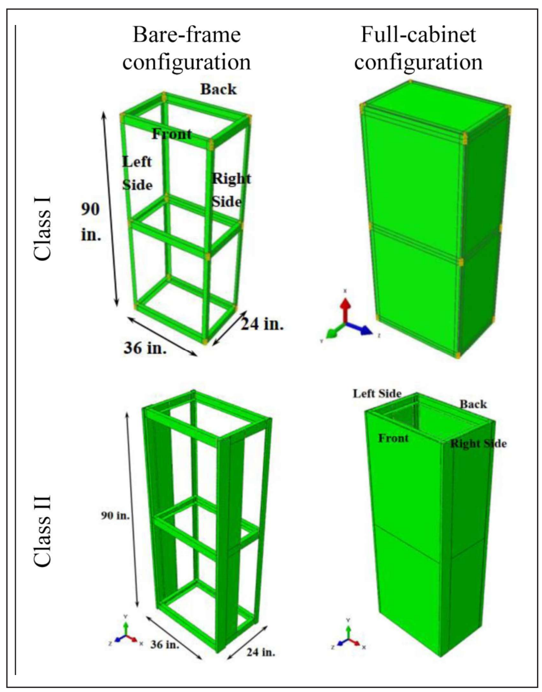


Figure 9. Cabinet models proposed, adapted from Lim.[18]

Table 1. Comparison between Class I and Class II configurations.

Structural components	Class I	Class II
Framing members	Hybrid Timoshenko beam model	Timoshenko beam model
Plates	Shell elements	Shell elements
Connections between framing members	Rotational springs and rigid beam constraints	Rotational springs and rigid beam constraints
Screw connection between plates and framing members	Rigid beam and warping constraints Translational springs	Rigid beam and warping constraints Translational springs Rotational springs

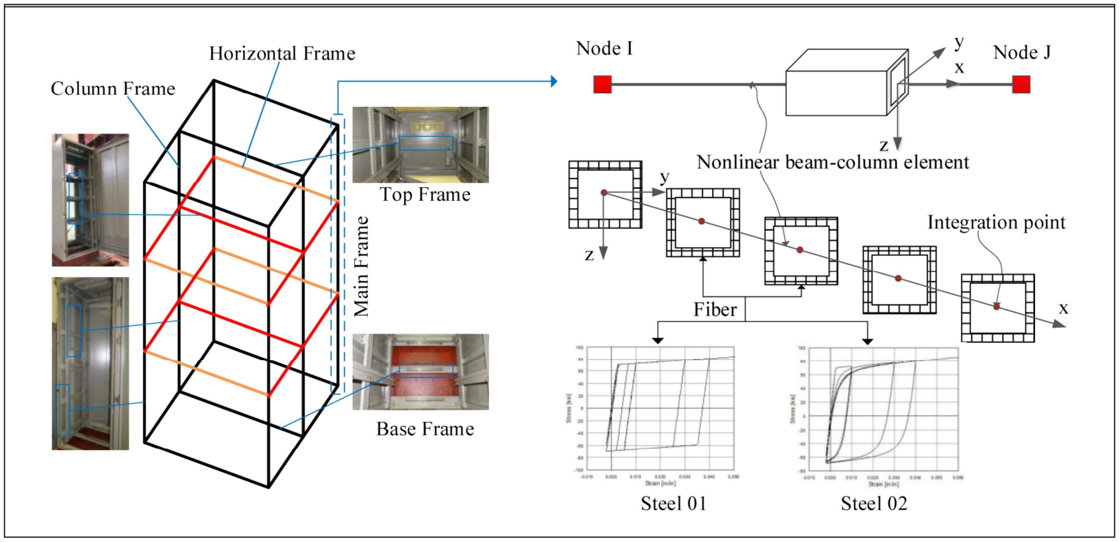


Figure 10. Cabinet models proposed, adapted from Tran *et al.*[37]

4. DISCUSSIONS

The development of the numerical models of the cabinet using different approaches is presented in this paper. The models using finite element approach are accurate to capture both local and global behavior of the cabinet. The global behavior of the frame members can affect the local mode shapes of the plates.

In practice, the simplified models are preferred to depict the global behavior rather than the full model which considers the local modes and requires time-consuming. However, it should be noted that the accuracy of the simplified models depends on the assumptions for idealization.

The application of the simplified models may be limit when considering the effects of local mode shapes or the occurring possibility of the buckling modes of sections.

5. CONCLUSIONS

This paper has collected and reviewed the methodologies used to develop the numerical model of the electric cabinet. A description of the important characteristics is presented first, followed by a description of modeling development. In each of them, the different strategies of structural modeling are discussed. The present paper has attempted to give an overview of the different research directions and it is expected to serve as a general reference and starting point to new researchers.

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