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Development of a Method to Generate a Simplified Finite Element Model for an Electrical Switchboard Cabinet

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Abstract

Electrical switchboards are one of the key pieces of equipment used in operations of most critical facilities such as hospitals and emergency services buildings. Unfortunately, past observations have shown that the switchboard cabinet and its contents may be vulnerable to damage or failure during an earthquake. An electrical switchboard cabinet is a complex structure typically constructed using cold-formed steel frame members enclosed by steel panels and containing a variety of switchgear and bus bars. The panels are usually fastened to the steel members by screws, and the steel members are connected together by bolts or screws. The structural behavior of the cabinet can be evaluated using shake table testing and/or high fidelity finite element models. However, these methods are relatively expensive, highly specific, and interpretation of the results may be difficult. Therefore, a method to formulate a simplified finite element model for the cabinet is proposed in this study. The simplified model consists of beam elements (Timoshenko), shell elements and springs. This model can be constructed and executed computationally at a lower cost, and interpretation of the results is a simpler assignment. The present model has the capability to capture the effect of warping deformation in the frame members and possible nonlinear behaviors of the cabinet, such as: local buckling at the end of frame members due to high bending moments, failure of the screw connections and buckling of the panels. The simplified model is validated using a high fidelity model of the cabinet under 1st-order and 2nd-order pushover analyses. Future work to incorporate structural models for the internal components is also discussed.

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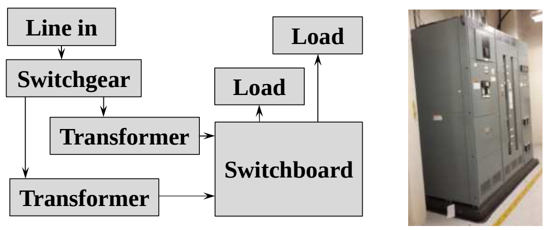
Introduction

Electrical power is transmitted from a generating station through a wide area transmission system and distribution subsystems leading eventually to end-users. At the facilities of a commercial end-user (e.g. hospital), the electrical power is distributed to different devices (loads) through transformers and switchboards consisting of switches and monitoring, distributing, and controlling equipment housed in cabinet-like structures (see Figure 1, which diagrams a simple configuration of electrical distribution and shows a switchboard installation). This electrical equipment is essential to maintaining the continuity and stability of electrical distribution within a facility and is therefore critical to the operation of most facilities.



(a) (b)

Figure 1 Typical switchboard cabinet system: (a) diagram of typical power distribution system at an end-user's facility, and (b) a group of switchboard cabinets.

Unfortunately, the electrical equipment in such cabinets is vulnerable to damage or failure during an earthquake. In general, there are two categories of failure that can happen to the equipment. The first is failure of the equipment caused by structural damage to the cabinets. Structural damage to an electrical cabinet can be further categorized into one of two broad types: 1) failure of unanchored/inadequately anchored cabinets, or 2) failure of properly anchored cabinets. The reconnaissance reports developed by EQE Engineering (EQE Engineering., 1991) and Goodno, et al. (Goodno et al., 2011) have shown that most of the structural damage to unanchored/inadequately anchored cabinets is caused by sliding or overturning of a cabinet and the failure of inadequate anchorage. In experimental tests, three types of failures have been observed related to properly anchored cabinets: 1) shearing/pull-out of panel-frame connections (screws), 2) deformation of enclosure panels, and 3) detachment of electrical components inside the cabinet. The second category is the failure of electrical equipment due to seismic vibration. This failure is related to the sensitivity of the internal electrical equipment to acceleration and displacement vibration intensity inside the cabinet. This paper will focus on the second category, specifically the performance of the cabinet structural system caused by seismic loading of properly anchored electrical cabinets.

Two methods are typically used to assess the behavior of an electrical cabinet: 1) an experimental shake table test and 2) a high fidelity finite element model of the cabinet in which all structural components of the cabinet are modeled explicitly using shell elements. Both of these methods are expensive, and interpretation of the results may be difficult, especially for groups of cabinets (see Figure 1.b). Therefore, several researchers have proposed simplified models of electrical cabinets to assess their dynamic behavior and performance. Gupta et al. (Gupta and Yang, 2002) adopted the Rayleigh-Ritz approach to develop the simplified models considering one global and one local mode. The results of their simplified models are validated by the results of detailed finite element models. Despite its accuracy and simplicity, the applicability of this method to other configurations of cabinets is unclear, especially with regard to how the model handles the variety of partially rigid connections between frames as well as connections between panels and frames.

Hur et al. (Hur, 2012) developed a framework to generate the simplified electrical cabinet models that consist of frame elements for framing members, shell elements for panels, and nonlinear springs for connections between frames and for connection between panels and frames. This approach allows a general application of the framework to different configurations of cabinets. Validation of this approach has shown that a model generated using this framework underestimated the first-mode experimental frequency by 1% and overestimated the second-mode experimental frequency by 20%. Despite its relatively accurate results and its more general applicability, some cabinet behaviors cannot be explained thoroughly based on this work. Specifically, 1) the definition of partially rigid connections between frames and the connections between panels and frames are not validated individually so the contribution to the modal properties of the cabinet of the modeling features (springs) developed for each type of connections cannot be distinguished; 2) omission of the effect of warping and shear deformations in the framing members to the behavior of cabinets; and 3) omission of the effect of elastic local buckling near the ends of a member that may exist when the cabinet is subjected to a dynamic load.

This study proposes a method to generate a simplified finite element model for electrical switchboard cabinets. The general framework proposed by Hur et al. is adapted and improved in this proposed method, in which the framing members and the panels are modeled with frame and shell elements, respectively. In addition, linear rotational springs and nonlinear translational springs are introduced to model the connection between framing members and the connection between panels and frames, respectively. Additional modeling features, such as rotational springs and constraint equations, are also introduced to the simplified model to improve the capability of the model to capture: 1) possible elastic local buckling behavior near the ends of the member, and 2) the effect of warping deformation of the framing members to the behavior of cabinets.

Structural Configuration of the Electrical Switchboard Cabinet

An electrical switchboard cabinet model, in which all structural components are built from plain sections (i.e. plain angles, plain channels, and flat panels with no folded edges), is selected for this study. Besides modeling a cabinet with relatively simple member configurations, this model is also selected as the first step to take to solve more complicated problems in an electrical cabinet with more complex configurations. The selected cabinet is constructed with four vertical posts with a plain angle section. These vertical posts are connected with beam members formed from a folded channel section and attached to the posts at the top, the mid-height, and the bottom of the cabinet using bolts/screws to form the framing system of the cabinet. This framing system is then enclosed by steel panels inserted in all eight openings in the sides of the frame and one panel at the top of the cabinet, The panels are attached using thread rolling screws attached at the four corners of each panel. Figure 2 shows the dimensions of the cabinet and the cross section used in this selected model, as well as the configurations of the connection between a panel and a framing member and the connection between the framing members.

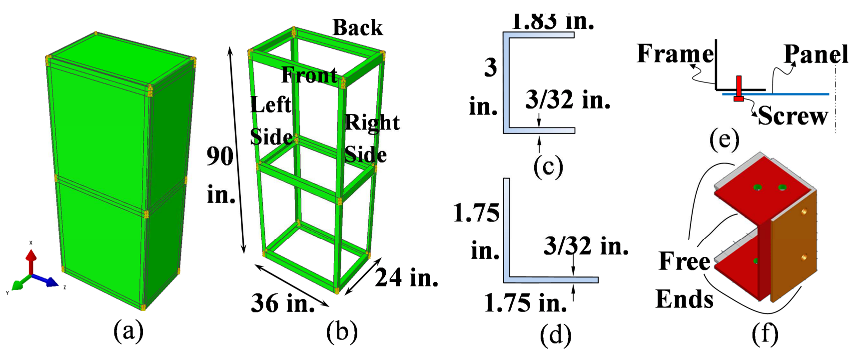


Figure 2 The switchboard cabinet under study: (a) the cabinet model enclosed by steel panels, (b) framing system of the cabinet model, (c) cross section of beam member, (d) cross section of vertical post, (e) connection between a panel and a frame, and (f) connection between framing members.

Selection of the Finite Element Model and Development of the Modeling Features for the Simplified Model

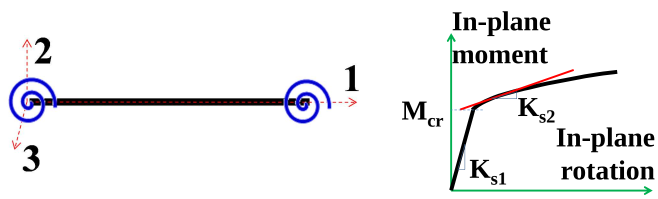
Framing members, panels and their connections to the framing members, and the connections between framing members are the main structural components of electrical switchboard cabinets. In the simplified model, each component is represented by finite element models and/or modeling features (i.e. springs, constraints). The material of the framing members and the panels is assumed to be linearly elastic, and the behavior of the connection between the framing members is assumed to be linear. These assumptions are taken because there is no clear evidence from earthquake reconnaissance surveys or shake-table tests that these components have yielded. The only sources of nonlinearities incorporated in the simplified model are: 1) failure of the connection between panels and framing members, 2) elastic buckling of the panels, and 3) possible elastic local buckling near the ends of the framing members due to high local bending moments.

Framing Members

The shear center of the channel and angle sections used in the framing members do not coincide with their sectional centroid, and as a result, these framing members will deflect and twist if loads are applied at the centroid. Furthermore, this twisting will also cause axial deformation (warping) in the members which may or may not be restrained. The members are also susceptible to elastic local buckling because the cross sections are thin. In structural analysis of the members, inclusion of this local buckling mode will further complicate the problems, and typically, finite element analysis using shell elements is used for this purpose because it can inherently capture the local buckling behavior of the members. However, this method becomes impractical once the complexity of the structure increases. Several researchers ((Silvestre and Camotim, 2003), (Wang and Errera, 1971), (Ayhan and Schafer, 2012)) have developed simpler models that have the capability to capture this local buckling behavior. Yet, the application of these methods for a more complex structure is still onerous.

Further simplification of the existing methods can be performed for a specific type of analysis, such as a pushover analysis. In the pushover analysis, the framing members of the cabinets are subjected to double curvature bending condition. In this condition, high stress is developed near the ends of the member, and it may eventually cause elastic local buckling in the members. To capture this local buckling behavior, a hybrid model consisting of Timoshenko beam elements commonly found in commercial structural analysis software along with a rotational spring at each end of a member is proposed (see Figure

3.a). The stiffness properties of the rotational spring can be generated based on the results of two different methods used to predict the behavior of a frame member subjected to double curvature bending: 1) a high fidelity method based on a finite element analysis of the member, and 2) a simplified method using an effective-width model of the buckled flange to describe its behavior. In the first method, finite element analysis of the member is performed using shell elements and including the nonlinear geometry effect so that local buckling can be captured in the analysis. In the second method, the end-rotation of the member is calculated for a prescribed value of the end-moment using a nonlinear effective-width model for the effective cross-sectional bending stiffness. The nonlinearity in the model arises when the cross sectional second area moment is reduced once the local bending moment exceeds the local buckling moment (M_{cr}) of the member. The reduced second area moment is calculated based on the effective cross section which is obtained by reducing the width of a compressed flange using a modified effective-width equation. In both methods, the behavior of the member is represented by an end-moment versus end-rotation curve characterized by the local buckling moment of the member and its stiffness prior to and after local buckling. More detailed explanations of the effective-width method and its validation can be found in (Lim et al., 2016).



(a) (b)

Figure 3 Hybrid frame model: (a) model schematic, (b) approximate sketch of the moment-rotation properties of the rotational springs

Using the results of either the finite element model or the effective-width prediction, the properties of the rotational springs in the hybrid model are calculated. The local buckling moment of the member is incorporated as the break point between the initial and the post-buckled segments characterized by the linear initial stiffness (K_{s1}) and nonlinear post-buckled stiffness (K_{s2}), respectively. Since, the member and the rotational springs are arranged in series with the member, this stiffness (see Figure 3.b) can be generated as follows:

$$K_s = \frac{K_{TS} K_B}{K_{TS} - K_B} \quad \text{Equation 1}$$

where

K_S = stiffness of the nonlinear spring,
K_{TS} = stiffness of the Timoshenko frame model, and
K_B = stiffness of the member subjected to double curvature bending.

Panel Model

Finite Element Model of the Panel

The panels of the electrical cabinets are constructed with thin-steel plates (typical thickness = 3/32 in.). These panels, together with the connection between the panels and the frames, are important to the structural rigidity of the cabinets. Furthermore, experimental tests of electrical cabinets have shown that significant deformation of the panels can occur during an earthquake. Therefore, shell elements are selected to model the steel panels because they have the capability to capture these behaviors.

Properties of Screw Connections Between Panels and Framing Members

The panels and the framing system of the electrical cabinet are usually connected by thread-rolling screws. In the cabinet model, this screw connection is modeled using the CONNECTOR–CARTESIAN, ALIGN feature in ABAQUS (see the two coincident nodes at point 1 and 3 in Figure 4). This feature rigidly constraints the rotational DOFs of two nodes (ALIGN) and defines zero-length translational springs (CARTESIAN) in three orthogonal directions (two shearing directions and one tensile direction) between two coincident nodes. The shearing properties of the springs are typically defined by the uniaxial load-deformation curve obtained from lap-splice tests using two thin plates connected with one or more screws. The lap splice tests of the screw connections have been conducted by many researchers to characterize their strength (Pekoz, 1990). However, studies that characterize the load-deformation behavior (e.g. initial stiffness) of the screw is still limited. Pham and Moen (Pham and Moen, 2015) developed empirical approaches in predicting the load-deformation characteristic of the connection. However, validations of those approaches to other types of screws are still needed.

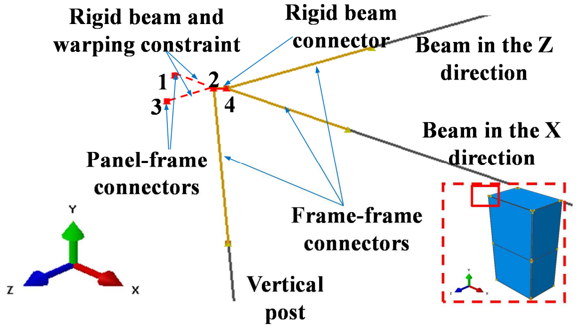
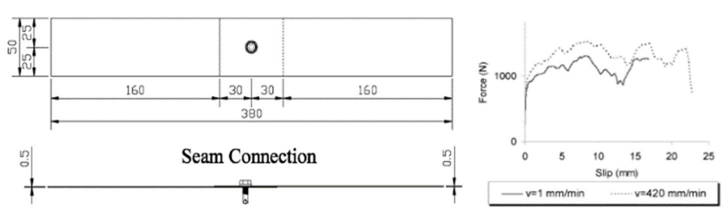


Figure 4 Detailed of locations of modeling features assigned to the simplified model

Due to limited information on the load-deformation behavior of screw connections, researchers typically conducted lap splice tests as part of their larger experimental test. Figure 5.a shows the lap splice tests on one type of screw connections conducted by Fulop and Dubina (Fulop and Dubina, 2004) as part of their experiments on a cold-formed shear wall. The tests were conducted with different loading rates, 0.039 in./min (1 mm/min) and 16.55 in./min (420 mm/min), to study the influence of time-dependent forcing functions on the behavior of screw connections. The results of the tests were scattered in nature and the average load displacement curves are shown in Figure 5.b. In an average (simplified) sense, the curves can be described as a linearly elastic (possibly rigid), perfectly plastic curve. This curve is characterized by two parameters: 1) initial stiffness, and 2) maximum load. Based on these characteristics, the load-deformation curve of the springs (in three orthogonal directions) used for the screw connection of electrical cabinet are defined. This assumption seems reasonable because it defines the 'failure' state (maximum load) of the screw connection although it may oversimplify the characteristics of the connections prior to and after the maximum load.



(a) (b)

Figure 5 Lap splice tests conducted by Fulop and Dubina: (a) specimen geometry (units in mm), and (b) average load-deformation curves obtained from the tests (figures courtesy of Fulop and Dubina)

One possible method to define the initial stiffness of the curve is based on an interpretation of the ECCS-TC7 guideline (ECCS, 1984) – "the design and testing of connection in steel sheeting and sections". In this guideline, it is stated that the maximum load of the connection can be defined as the load at a deformation value of 3 mm (0.118 in.). According to this information, the initial stiffness of the screw connection is assumed as the ratio between the maximum load and the deformation value of 3 mm (0.118 in.). This approach applied to calculate the initial stiffness of screw connection in shear is also adapted to define the initial stiffness in tension. Hence, the maximum shear and tensile load of the screw connection can be calculated based on Equation 2 and 3 as defined in AISI S100 (AISI, 2007).

$$F_{shear} = \min\left(4.2\sqrt{\left(t_2^3 d\right)}F_{u2}, 2.7\, t_1\, d\, F_{u1}, 2.7\, t_2\, d\, F_{u2}\right) \qquad \text{Equation 2}$$

$$F_{ten} = \min\left(0.85\, t_c\, d\, F_{u2}, 1.5\, t_1\, d_w^{'}\, F_{u1}\right) \qquad \text{Equation 3}$$

where

F_{shear} = shear strength of the screw connection
t_2 = thickness of member not in contact with screw head
d = diameter of the screw
F_{u2} = tensile strength of member not in contact with screw head
t_1 = thickness of member in contact with screw head
F_{u1} = tensile strength of member in contact with screw head
F_{ten} = tensile strength of the screw connection
t_c = lesser of the depth of penetration and the thickness t_2.
$d`_w$ = minimum of the diameter of the head of screw and 0.5 in. (12.7 mm).

Development of Constraint Equations for the Panel Attachment

Rigid beam and warping constraints are assigned to pairs of points at the centroidal axis of the vertical posts and the flanges of the posts where panels are attached to them. Figure 4 shows two pairs of points (points 1-2 and 2-3) in which these constraints are imposed at the top left corner of the cabinet. Rigid beam constraints are applied to restrict the deformation of the points on the flanges based on the beam kinematic assumption that plane sections remain plane. Additional warping deformation constraints are imposed on those points because the vertical posts will warp when the cabinet is subjected to lateral load. The warping deformation of the vertical posts is calculated based on an assumption that a vertical post is subjected to a linearly varying internal torsional force distribution induced by in-plane double-curvature bending of the post. The boundary conditions for the post are assumed to be warping-free and partially fixed at both ends. The partial fixity is due to the out-of-plane bending stiffness of the beam members connecting at the ends of the vertical post. The warping constraint equation is written as the axial deformation of a point at the flange of the vertical post due to a unit torsional rotation at the centroid of the post.

Connection Between Framing Members

The connection between framing members is represented as linear rotational springs in three orthogonal directions assigned to each member coincident at a joint (see the frame-frame connectors in Figure 4). These springs are modeled by the CONNECTOR–JOIN, ROTATION feature in ABAQUS. This feature rigidly constrains all translational DOFs (JOIN) and assigns rotational springs in three orthogonal directions (ROTATION). The stiffness of the springs for a member is obtained by imposing a unit rotation in each orthogonal direction to that member while fixing the other members coincident at the joint. These members are modeled using shell elements, and their length is about 5 – 7 % of their total length. The members are connected with FASTENER features in ABAQUS by assuming a BEAM interaction that connects all DOFs of the connecting nodes located at the positions of the screws/bolts. Furthermore, the nodes at the free end of each member (see Figure 2.f) are constrained to its centroid at that end using the BEAM MPC (Multi Point Constraint) feature in ABAQUS, and the centroids are then fixed in all DOFs, except: 1) when a unit rotation (besides torsional rotation) is applied to a member to generate the stiffness of the springs; the centroid of that member is only fixed in the direction corresponding to the applied rotation, and 2) when a unit torsional rotation is applied to a member to generate the torsional stiffness of the springs; distributed couplings are assigned (instead of MPC) in the torsional DOF between the nodes at the free end of the member and its centroid at that end to impose a warping free boundary condition, and the centroid is fixed only in the torsional direction. In the MPC feature, the DOFs of the slave nodes are eliminated. Therefore, relative displacements between the slave nodes are not possible. Meanwhile, in the distributed coupling, the DOFs of the slave nodes are not eliminated. The force/moment applied at the master node is distributed to the slave nodes in an average sense. In this coupling, relative displacements between slave nodes are possible. Afterward, the stiffness of the springs in each direction for each member coincident at the joint is calculated as the ratio of the reaction moment at the centroid to the corresponding applied unit rotation.

In addition to the rotational springs, the finite-joint size of the connection between framing members is also considered in the simplified model. The size of the joint is the same as the size of the connection models used to generate the properties of the rotational springs. Furthermore, a rigid beam constraint is also assigned between a point (point 4 at Figure 4) at the intersection of the beam members and a point (point 2 at Figure 4) at the extension of the centroidal axis of the vertical post.

Validation of the Simplified Models to High Fidelity Models of the Cabinets

Development of the High Fidelity Models

In the high fidelity models, all structural components of the cabinet (framing members and/or panels) are modeled explicitly using shell elements in ABAQUS. The framing members are connected together using the FASTENER–BEAM feature. In addition, three translational springs with properties the same as those assigned to the simplified model are used to represent the connections between the panels and the frames. These translational springs are modeled using the CONNECTOR–CARTESIAN, ALIGN feature in ABAQUS.

Development of the Simplified Models

The simplified models are developed using the methods described in the previous section. Timoshenko beam elements and shell elements are selected to model the framing members and panels, respectively. Next, in-plane rotational springs with properties generated from the effective-width prediction for the framing member are attached at each end of the framing members to handle the elastic local buckling behavior. The framing members are then connected with rigid beam constraints and rotational springs in three orthogonal directions (see rigid beam connector and frame-frame connectors in Figure 4), in which their properties are generated from detailed finite element models of the joint. Furthermore, before attaching panels to the cabinet, rigid beam and warping constraints are assigned to pairs of points between the centroid of the vertical posts and the points of attachment of the panels to the flanges. Lastly, the panels are connected to the attachment points with the zero-length translational springs in three orthogonal directions (see panel-frame connectors in Figure 4).

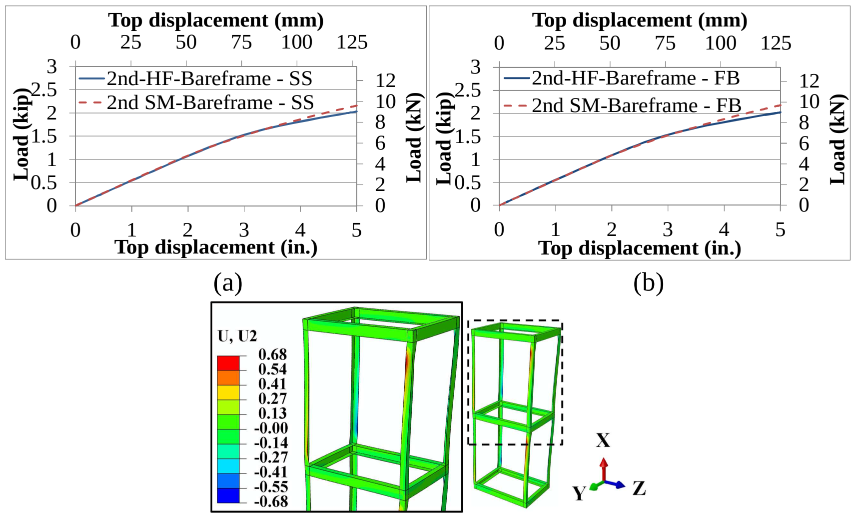
Validation of the Simplified Models

Two configurations of the electrical cabinet model are considered in this study. The first configuration is the cabinet model without panel enclosures (bare-frame), and the second configuration is the cabinet model with panel enclosures (full-cabinet). The bare-frame model is needed to validate the spring properties defined for the connection between framing members. High fidelity (HF) and simplified (SM) models are then developed for each configuration of the cabinet. The models are fixed at the four bottom cabinet corners and subjected to pushover analyses in the front-back (FB) and left-right side-to-side (SS) directions (see Figure 2.b) of the cabinet by applying a displacement at the top of the cabinets. The analyses are performed by including the nonlinear geometric effects (2^{nd} order) and not including them (1^{st} order). Inclusion of the 2^{nd} order effects enables the models to capture the local buckling behavior of the framing members and panels.

Validation of the Bare-frame Models

In the first order analyses, the bare-frame models behave in a linear elastic manner. Comparisons of the stiffness of the pushover curves obtained from the simplified and the high fidelity model show that the simplified models underestimate the elastic stiffness by -0.3 % and -1.45 % in the SS and FB directions, respectively. These results show the accuracy of the spring properties developed for the connection between framing members.

In the second order analyses, elastic local buckling occurs near the ends of the vertical posts for both pushover analyses in the SS and FB directions. The local buckling reduces the rigidity of the bare-frame cabinet model as shown in the pushover curves in Figure 6.a and b. The simplified models are able to reproduce the initial stiffness of the high fidelity models. However, they slightly overestimate the post buckling stiffness of the high fidelity models. It should be noted that the vertical posts are constructed from a plain angle section and subjected to unsymmetric bending. Meanwhile, the stiffness-reducing effect incorporated into the simplified model through a rotational spring at each end of the vertical posts is only applied in the in-plane bending direction. Addition of rotational springs with coupled properties (in-plane moment and out-of-plane rotation) may improve the performance of the simplified models. However, the improvement may not be necessary for electrical switchboard cabinet because: 1) the electrical cabinets are most likely enclosed by panels which may change the behavior of the cabinet and 2) the simplified models are able to predict the behavior of the high fidelity model accurately up to a reasonable top displacement value of cabinet (e.g. 3 in.).



(c)

Figure 6 Pushover curves for the bare-frame models under: (a) 2nd order analysis in the SS (Z) direction, and (b) 2nd order analysis in the FB (Y) direction, as well as (c) elastic local buckling near the ends of framing members (pushover analysis in the SS direction)

Validation of the Full-cabinet Models

In the first order analyses, the behavior of cabinet models is characterized by the ‘failure’ of connections between panels and frames in shear. The ‘failure’ state is defined when the loads at the springs defining the connections have reached the perfectly plastic region. Comparisons between the pushover curves obtained from the simplified and the high fidelity models show that the simplified models are capable of capturing the initial stiffness, the ‘failure’ load and the post-failure stiffness of the high fidelity models (see Figure 7.a and b). In the second order analyses, the behaviors of the cabinet models are defined by multi-linear curves (see Figure 7.c and d). The main stiffness reduction is caused by two factors: 1) buckling of panels (see Figure 7.e), and 2) ‘failure’ of the connection between panel and frame. After the buckling of the panels, the compressed vertical posts are subjected to local deformation as shown in Figure 7.f. This local deformation may be caused by the axial force instead of bending moment in the member since this deformation is spread out along the length of the posts. However, the stiffness reduction caused by this local deformation is not significant compared to the overall behavior of the cabinet. It is evident by the stiffness of the pushover curves after the buckling of panels which is almost the same as before the ‘failure’ of the connections. Therefore, including this behavior in the simplified model may not be significant.

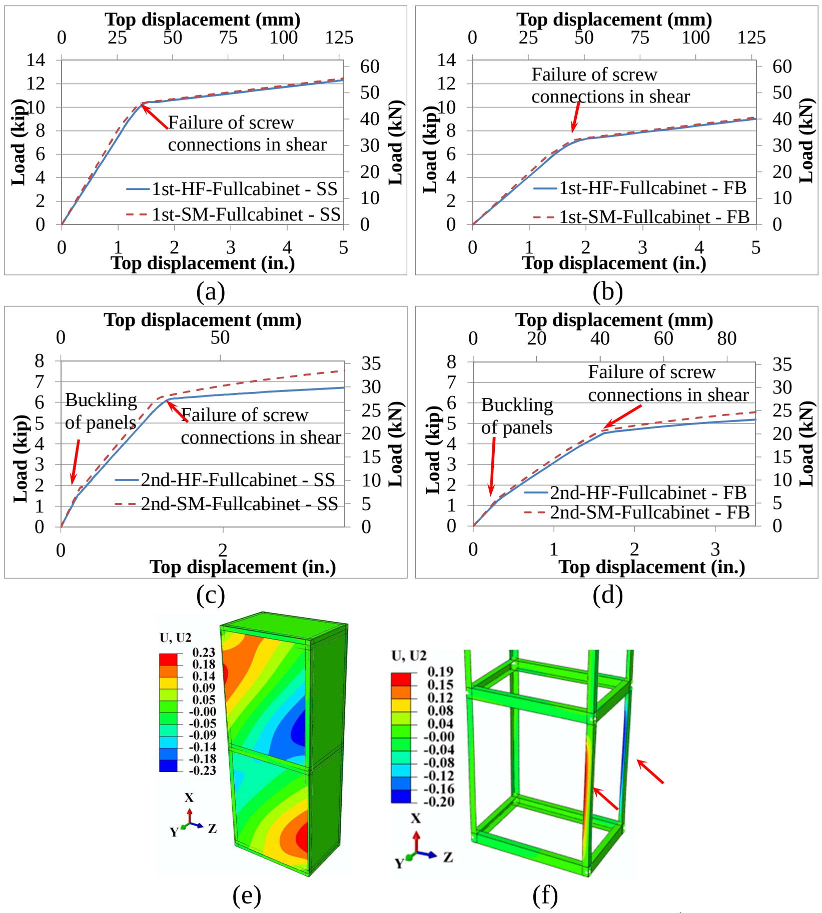


Figure 7 Pushover curves of the full-cabinet models under: (a) 1st order analysis in the SS (Z) direction, (b) 1st order analysis in the FB (Y) direction, (c) 2nd order analysis in the SS (Z) direction, and (d) 2nd order analysis in the FB (Y) direction, as well as (e) out-of-plane deformation of the panels at the buckling load (pushover analysis in the SS direction), and (f) local deformation in the flanges of the compressed vertical posts (pushover analysis in the SS direction)

In general, the load-displacement curves produced by the simplified models are in a good agreement with the curves produced by the high fidelity models. The simplified models overestimate the buckling load of the panel, the ‘failure’ load of the connection, and the initial and the post buckling stiffness of the cabinet by less than 10% for both the SS and FB directions. However, the predictions of the stiffness after the ‘failure’ of the connections are about +12% in the FB direction and about twice of the stiffness of the high fidelity model in the SS direction. Despite the overestimation of the stiffness after the ‘failure’ of the connections, the load (base shear) at the cabinet is overestimated by only about 10% or less for a realistic maximum top displacement of the cabinet (e.g. 3 in.). This indicates that the load carrying capacity of the cabinet is significantly reduced after the ‘failure’ of the connections.

Conclusions and Future Works

This study has presented and validated a method to generate a simplified finite element model of an electrical switchboard cabinet that has the capability to capture nonlinear effects caused by: 1) ‘failure’ of the connections between panels and frames, 2) elastic buckling of panels, and 3) possible elastic local buckling near the end of members due to double curvature bending. Future work will include application of the method to a more complex configuration of electrical cabinets and study of the dynamic characteristics of a single cabinet and groups of cabinets by introducing the electrical equipment into the cabinet models.

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Appendix - Notation

d = diameter of the screw
$d`_w$ = minimum of the diameter of the head of screw and 0.5 in. (12.7 mm)
F_{shear}, F_{ten} = shear and tensile strength of the screw connection, respectively
F_{u1}, F_{u2} = tensile strength of member in and not in contact with screw head, respectively
K_B, K_s = stiffness of the member and the rotational springs, respectively
K_{s1}, K_{s2} = initial and post buckling stiffness of the rotational spring
K_{TS} = stiffness of the Timoshenko beam model
M_{cr} = buckling moment of the member
t_1, t_2 = thickness of member in and not in contact with screw head, respectively
t_c = the lesser of the depth of penetration and the thickness t_2.