ABSTRACT

CROWDER, NICHOLAS COLE. Improving Digital Engineering Workflows by Enabling BIM Interoperability for Structural Analysis and Facilitating Accurate Modeling of Building, Equipment, and Piping Systems. (Under the direction of Dr. Abhinav Gupta and Dr. Kevin Han.)

Seismic risk assessment of building, piping, and equipment systems utilizes analytical models for structural analysis. However, accurate modeling of seismic behavior for these systems presents several technical and logistical challenges, such as multidisciplinary data exchange and workflows, modeling assumptions of boundary conditions for equipment, and accurate modeling for coupled systems analysis. Coupled analysis for building, piping, and equipment systems contributes to confidence in seismic risk assessment, but modeling of these coupled systems is often overlooked due to logistical, time, and budgetary constraints in traditional engineering workflows. Therefore, there is a need to both further study coupled systems analysis as well as enable the quick but accurate modeling of such coupled systems through innovations in digital engineering workflows. This dissertation presents research that studies the modeling complexities of primary and secondary systems as well as presents novel innovations in digital engineering workflows that enable quick and accurate modeling of such coupled systems, particularly for building, piping, and equipment systems. The first half of this dissertation studies the effects of boundary conditions on the dynamic behavior of equipment, specifically switchgear mounting and electrical cabinet anchorage. The second half of this dissertation develops a framework and associated tool that enables BIM interoperability for structural analysis of structural building systems and non-structural piping systems. Future research efforts stemming from the work presented in this dissertation will aim to facilitate the ease, efficiency, and accuracy of coupled systems analysis in digital engineering workflows.

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Improving Digital Engineering Workflows by Enabling BIM Interoperability for Structural Analysis and Facilitating Accurate Modeling of Building, Equipment, and Piping Systems

by
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DEDICATION

To my Parents and Grandparents, whose support brought me to where I am today.

BIOGRAPHY

Nicholas Crowder was born in Fairfax VA and raised in the Raleigh NC area. He enrolled in the First Year College program at North Carolina State University in 2013 before transferring to the undergraduate program in Civil Engineering. He earned his Bachelor of Science in Civil Engineering with Valedictorian honors in 2017. He continued his studies at NCSU as a graduate student in the Civil Engineering department under the mentorship of Dr. Abhinav Gupta and Dr. Kevin Han. During his doctoral studies, he served as a Graduate Research Assistant and Teaching Assistant.

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CHAPTER I

Introduction

I.1 Introduction

Modeling seismic behavior accurately helps to instill con dence in the safety and risk assessment of critical infrastructure such as nuclear power plants and, in some cases, can reduce excessive conservatism in design. For example, coupled analysis of building-piping-equipment systems has been shown to produce less conservative results than the traditional approach of uncoupled analysis, which considers all these systems separately [1, 2]. In addition, modeling assumptions of the boundary conditions for equipment, such as the mounting arrangements for switchgears in substations or relays in electrical cabinets, can have a signi cant impact on dynamic behavior for seismic analysis. However, accurate modeling of seismic behavior for these systems presents several technical and logistical challenges, such as multidisciplinary data exchange and work ows, modeling assumptions of boundary conditions for equipment, and accurate modeling for coupled systems analysis.

Seismic risk assessment is inherently a multidisciplinary endeavor, involving specialized engineers that must communicate with one another, such as structural engineers and nonstructural piping designers. However, digital data exchange and communication between the architectural, engineering, and construction spaces can be logistically di cult and time-consuming. For example, an industry report by McGraw Hill showed that the value/e ort ratio for engineering analysis with building information modeling (BIM) is very low [3]. According to the same survey, the value/e ort ratio for structural analysis with BIM is so low that structural designers and engineers would save time by creating their own structural analysis models instead of relying on those generated by BIM. Therefore, there is a need to streamline digital engineering work ows for structural analysis through improvement in interoperability between architectural design and structural analysis domains across disciplines, with special attention made to the modeling assumptions of critical structural and nonstructural systems.

Given the combined understanding that (1) accounting for equipment-structure interactions through coupled modeling of building, piping, and equipment systems contributes to accuracy in seismic risk assessment and that (2) the modeling the interactions among these coupled systems is often overlooked due to logistical, time, and budgetary constraints in traditional engineering work ows, there is a need to both (1) further study the need for coupled systems analysis as well as (2) enable the quick but accurate modeling of such coupled systems through innovations in digital engineering work ows.

I.2 Background

Improving virtual engineering work ows and accurately modeling connections and supports of building, piping, and equipment systems would aid in the design and analysis of safety systems for critical infrastructure such as nuclear power plants. Such improvements in structural analysis would help save time and cost for construction projects that rely on digital data exchange while maintaining con dence in design and analysis accuracy.

I.2.1 The Need for Coupled Analysis: Modeling Building and Piping Systems

The current state-of-the-practice for piping design in the nuclear industry prescribes that each piping system is treated in isolation from the structural building components or major equipment to which it is connected. Historically, uncoupled analysis has been considered su cient for light secondary systems such as piping. However, much work has been published over the past two decades that highlights the importance of equipment-structure interaction (ESI). Studies have shown that uncoupled analysis of piping systems may result in excessive conservatism as compared to a coupled analysis approach that considers interactions between piping systems and the other connected systems[1,2,4-7]. Such excessive conservatism leads to increased costs of design, construction, and

maintenance. A summary of some other important aspects that are unaccounted for in conventional uncoupled piping system analysis are listed below:

- Interaction of resonant modes between piping and the support structure
- Phase information between supports of piping xed at multiple elevations in multi-story buildings.
- High pipe stresses caused by relative support motion (in the conventional approach, a conservative method must be employed, known as seismic anchor motion analysis)
- Nonclassical damping e ects that occur when the damping characteristics of primary and secondary systems are di erent.

However, combining the designs of building and piping systems for coupled analysis is not straightforward because the connectivity details do not facilitate incorporating the piping systems into the building model easily. Careful attention must be paid to the boundary conditions of such nonstructural systems such as piping and equipment to properly capture the dynamic interactions among coupled systems.

I.2.2 Modeling Considerations for Secondary Systems: E ects of Boundary Conditions on the Dynamic Behavior of Equipment

Critical safety-related instruments, such as relays mounted within electrical cabinets and switchgears within substations, must be seismically quali ed to ensure functionality during and after an earthquake. Careful consideration should be made when modeling their boundary conditions, as this can have a great e ect on dynamic behavior. For example, many studies consider cabinet nite element analysis models where the cabinet is rigidly anchored at the base with xed supports. However, studies have shown that the exibility of the cabinet mounting arrangement can signi cantly a ect dynamic behavior [8 14]. Similarly, when switchgear equipment undergoes shake table testing for seismic quali cation, the equipment is rigidly mounted on testing platforms with continual support.

However, the in-situ field installation conditions oftentimes do not exhibit such rigidity in mounting and may even exhibit nonlinear behavior, such as base uplift and impact. Proper modeling of the support conditions of switchgears in analytical models can help capture such complex and unaccounted-for nonlinearity. The mounting arrangement of equipment should be investigated to ensure best modeling practices for seismic analysis, especially when such equipment is connected to structural building components as part of a large coupled system.

I.2.3 Need for Facilitating Design-Construction Integration through BIM Interoperability

Design changes during construction projects can result in increased costs and schedule delays. For example, recent nuclear construction projects experienced delays and cost overruns that were caused by redesigns requiring regulatory approval, which is a common pattern that negatively affects vendors and customers in the nuclear industry [15, 16]. The problems associated with managing design changes and construction deviations are exacerbated by the lack of commercial software interoperability for design and analysis. A 2021 industry survey among design and construction professionals who use BIM in their projects reveals that "Improved Interoperability Between Software Applications" is the top technical factor that would help increase the benefits of using BIM [17]. There is a need for integrated design-construction software solutions that will help facilitate risk-informed decision-making for construction and design deviations.

Facilitating quick and accurate model data exchange and interoperability between architectural and structural analysis software would help facilitate design-construction integration. However, no standardized process exists for a seamless data exchange between BIM and structural analysis software. Existing methods for BIM interoperability for structural analysis face technical challenges, such as joint disconnection, element embedment, element overlapping, and missing information [18].

There is a need to facilitate interoperability between BIM and structural analysis software without loss of necessary structural information, both for primary structural building systems and for secondary non-structural systems such as equipment and piping.

I.3 Research Objectives

The primary objectives of this research are to further study the need for coupled systems analysis by considering the modeling complexities of primary and secondary systems as well as to enable the quick but accurate modeling of such coupled systems through innovations in digital engineering work ows. Therefore, the key objectives of the proposed research are outlined as follows:

- Study the e ects of boundary conditions on the dynamic behavior of equipment, speci cally switchgear mounting and electrical cabinet anchorage.
- Develop a framework and associated tool that enables BIM interoperability for structural analysis of structural building systems and non-structural piping systems

I.4 Research Findings and Organization of Dissertation

This dissertation consists of six chapters. Chapter I introduces the problem being studied and discusses the objectives of the research. Chapter II, Chapter III, Chapter IV, and Chapter V address the research objectives presented in Section I.3. Chapter VI presents summaries and conclusions of the research and proposes recommendations for future work. The novel contributions of the technical chapters are summarized below.

- Chapter II presents a case study for a proof-of-concept framework for considering modeling geometric nonlinearities of support structures for seismic quali cation of switchgear equipment. The procedure outlined in this chapter shows the necessity and practicality of performing nonlinear analysis on critical nonlinear support

elements within the broader framework of seismic quali cation of the full equipment assembly. Chapter II is adapted from a conference paper presented at SMiRT25 [19].

- Chapter III presents a theoretical exploration of the e ects of nonlinear mounting arrangements on the high-frequency response of in-cabinet response spectra. This study concludes that the seismic quali cation of electrical devices may be adversely a ected if localized nonlinearities are not considered. Chapter III is adapted from a journal paper that has not yet been published.
- Chapter IV presents and tests a new BIM interoperability tool for improving IFC-based model data exchange between architectural design and structural analysis for building structures. The tool is tested against IFC les of architectural building designs exported from commercial CAD software and succeeds in showing marked improvement for IFC-based CAD-to-CAE interoperability over existing practice.
- Chapter V presents and tests additions to the BIM interoperability tool introduced in Chapter IV by incorporating compatibility for BIM piping models. Similar to the results for building models in Chapter IV, the tool also shows marked improvement for IFC-based model data exchange of piping designs.

CHAPTER II

Modeling Geometric Nonlinearities of Support Structures for Seismic Quali cation of Switchgear Equipment

II.1 Introduction

High-voltage substation switchyards are critical junctions in the power transmission sector of the electric power grid. Gas-insulated high-voltage switchgear (GIS) equipment are enclosed by metal ducts that house critical electrical components such as circuit breakers and disconnect switches. Sulfur hexa uoride gas insulates the electrical components. Figure II.1 shows a picture of a typical GIS equipment assembly.

Steel framing and anchored plates support heavy switchgear equipment. Critical support structures for high-voltage substation equipment must be quali ed for appropriate seismic loads in order to ensure power equipment safety and reliability during seismic events. Structural nonlinearities in the switchgear supports must be considered in a seismic response assessment of such systems.

Figure II.1: Typical Gas Insulated Switchgear (GIS)

II.2 Seismic Quali cation Methodology Background

The current industry practice for seismic quali cation of switchgear equipment follows the guidelines prescribed in IEEE-693 (2005) [20]. These guidelines mandate that high-voltage equipment above 169kV be quali ed by time history shake table testing for strength and functionality criteria. Equipment under 169kV may be analytically quali ed via nite element (FE) modal time history analysis or static coe cient analysis, both of which only

satisfy strength criteria. Figure II.2 shows the accepted quali cation methods based on switchgear voltage classi cation.

Figure II.2: IEEE-693 (2005) [20] Seismic Quali cation Methods by Voltage Classi cation

Seismic quali cation by time history shake table testing can only be performed on switchgear sub-assemblies or single units, as shown in Figure II.6a. Shake table tests cannot test entire bays of interconnected equipment, for reasons of practicality. Therefore, shake table quali cation tests do not account for the interactions between multiple switchgear units nor the e ect of di erences in the mounting arrangement between the test set-up and eld installation.

Much of the available literature on the dynamic behavior of interconnected substation equipment has involved air-insulated switchgear (AIS) substations [21, 22]. However, in recent years, AIS equipment have been replaced by gas-insulated switchgear (GIS) for their compactness and cost e ectiveness in regards to long-term maintenance. Understanding the dynamic behavior of these GIS units is critical for seismic

quali cation. Bargigia et al. [23] compares and contrasts the various approaches for the quali cation of standardized GIS units, and their work stresses the importance of inter-component interaction and soil foundation interaction for evaluation of switchgear dynamic behavior.

Chatterjee [24] recognizes the lack of a comprehensive quali cation methodology for full-scale switchgear equipment assemblies within the existing literature and industry guidelines. Chatterjee [24] develops a comprehensive quali cation methodology for GIS substation equipment that incorporates shake table test data and nite element modal time history analysis, all in accordance with IEEE 693 (2005) [20] principles and guidelines.

II.3 Case Study: 230kv Gas-Insulated Switchgear Seismic Quali cation

The authors of this study adopt the methodology of Chatterjee [24] for the full-scale seismic quali cation of a 230kV ELK14 GIS switchyard. However, structural nonlinearities present in the GIS supports do not allow for the exclusive use of linear analysis methods as prescribed in IEEE 693 (2005) [20] and implemented by Chatterjee [24]. A detailed model of the complete GIS-building including all switchgear equipment, supports, and enclosures together with nonlinearities at the GIS support is computationally impractical. Moreover, consideration of nonlinearities in such a detailed model do not add value in the context of GIS-equipment quali cation. The equipment quali cation is based on the evaluation of maximum accelerations at di erent locations in the GIS and comparison of the maximum values with the corresponding values recorded in shake table testing. Nonlinearities at the base of GIS would only tend to result in lower values of the accelerations compared to the values evaluated from a linear analysis. On the contrary, consideration of nonlinearities at the base is important for assessment of appropriate design loads in the anchor bolts. Therefore, we use two di erent nite element (FE) models for the complete seismic quali cation of the 230kV GIS equipment.

1. Linear analysis of the complete GIS-building FE model (includes all switchgear equipment, supports, and enclosures)
2. Nonlinear analysis of only the decoupled circuit breaker (CB) support structure FE model

The primary focus of this chapter is to discuss the specialized nonlinear analysis methods implemented to qualify the nonlinear mounting structure of the CB equipment. The CB support structure requires a separate, specialized nonlinear nite element analysis in order to capture accurate anchor bolt design forces for seismic quali cation. The separate nonlinear analysis of the CB supports supplements the broader linear time history analysis of the complete GIS-building FE model.

II.3.1 Equipment Description

The switchgear equipment is a gas insulated switchgear (GIS) type ELK14 with a nominal system voltage of 230kV. Galvanized steel supports anchored to an elevated concrete oor slab support nine bays of GIS equipment. Figure II.3 shows a model of the 230kV GIS equipment assembly.

Figure II.3: Model of 230kV GIS Assembly

II.3.2 Nonlinear Circuit Breaker Mounting Structure

Circuit breaker (CB) assemblages for the 230kV GIS are supported by sti ened I-beam steel sections with bottom anges resting at on the concrete oor slab and anchored by steel plates welded to the bottom ange, as shown in Figure II.4. The CB mounting condition introduces a contact surface problem involving nonlinear support conditions; therefore, the CB support structure requires a separate nonlinear nite element model in order to capture accurate anchor bolt forces for seismic quali cation.

Figure II.4: Circuit Breaker Support Structure

II.3.3 Building Description

230kV GIS equipment is installed indoors on top of an elevated concrete oor slab supported by a concrete moment frame. The reinforced concrete frame consists of structural slab, beams, and columns with 4000 psi strength. The elevated oor is enclosed by a climate-controlled pre-engineered metal building (PEMB) enclosure that houses the GIS equipment. The lateral load resistance system consists of a metal rigid frame in the transverse direction, metal cross bracing in the longitudinal direction, and reinforced concrete special moment frame in both the transverse and longitudinal directions. Refer to Figure II.5a for an isometric view of the PEMB framing layout, and Figure II.5b for a detailed section view of the GIS-building system.

(a) 230kV Switchgear Building Framing Isometric View

(b) 230kV Switchgear Metal Building Section View

Figure II.5: 230kV GIS Metal Building

II.4 Linear Analysis of Complete GIS-Building Assembly

Seismic quali cation for the 230kV ELK14 GIS switchyard utilizes the comprehensive seismic quali cation methodology pioneered by Chatterjee [24]. The quali cation process

begins by considering a subassembly of GIS equipment previously tested on a shake table for both sine sweep input as well as IEEE-693 (2005)[20] recommended time histories, as shown in Figure II.6a. Sine sweep tests identify the dynamic characteristics of the tested equipment. The shake table time history runs qualify the electrical functionality of the tested equipment for high seismic level input.

The results of the sine sweep shake table tests are used to develop a nite element (FE) model of the GIS test setup that reconciles well with the test data (Figure II.6b). The FE model of the tested equipment provides an important basis for developing the FE model of the complete eld assembly (Figure II.6c). After accounting for the structural di erences between the test set-up and eld design, a FE model of the full 230kV GIS eld assembly and building structure is developed to represent eld conditions (Figure II.6d).

Analysis of the 230kV GIS-building FE model is conducted by tri-axial time history analysis using IEEE- 693 (2005)[20] compatible ground motions. Post-processing of support stresses produces acceptable design loads for all GIS equipment except for the CB support structure, which cannot be analyzed linearly. The CB support beam anchorage requires a separate, specialized nonlinear FE analysis for seismic quali cation in order to capture accurate anchor bolt design forces.

II.5 Nonlinear Analysis of Circuit Breaker Supports

The circuit breaker (CB) mounting structure exhibits nonlinear support conditions. The CB support beam anchorage requires a separate, specialized nonlinear nite element analysis for seismic quali cation in order to capture accurate anchor bolt design forces.

II.5.1 Circuit Breaker Mounting Structure Description

Circuit breaker (CB) assemblages are supported by sti ened I-beam steel sections with bottom anges resting at on the concrete oor slab and anchored by steel plates welded

(a) Single GIS Unit Shake Table Test

(b) FE Model of GIS Test Setup

(c) FE Model of GIS Field Assembly

(d) FE Model of complete GIS-building System

Figure II.6: Finite Element (FE) Model Development for 230kV GIS Linear Analysis

to the bottom ange. See Figure II.4 for computer-aided design (CAD) renderings of the CB support mounting arrangement. The CB mounting condition introduces a contact surface problem involving nonlinear support conditions.

II.5.2 Motivation for Decoupled Analysis

In the complete GIS-building FE model, the bottom anges of the circuit breaker 2D shell support beams are meshed continuously along the concrete oor slab elements, as shown

in Figure II.7. This modeling assumption simpli es the analysis for the overall GIS and steel support response to time history excitation. However, capturing accurate anchor bolt forces for the CB mounting structure and anchor bolts requires a closer examination of the physical nonlinear mounting conditions. The CB support beam anchorage is decoupled from the building model, nonlinear support elements are added to the CB support beams, and a nonlinear time history analysis is conducted for the sole purpose of capturing accurate forces acting on the CB support beam anchor bolts. The decoupled GIS CB support beam analysis procedure is outlined in the following section.

Figure II.7: CB Support Meshing for GIS-Building Linear Analysis

II.6 Method of Analysis for Nonlinear Circuit Breaker Supports

The circuit breaker (CB) support structure requires a separate, specialized nonlinear nite element time history analysis for seismic quali cation in order to capture accurate anchor bolt design forces.

II.6.1 Development of Decoupled FE Model of CB Support Structure

The development of the decoupled nite element (FE) model of the CB support structure follows the procedure outlined below:

1. Run linear modal time history analysis of complete GIS-building model using IEEE

compatible ground motions, as graphically summarized in Figure II.6. This analysis satis es all other seismic quali cation criteria aside from analyzing the nonlinear CB support beam anchor bolts.

2. Identify most highly stressed CB support assembly. See Figure II.8.
3. Decouple CB support assembly from the complete GIS-building FE model.
4. Add nonlinear compression-only gap-link elements to capture contact surface e ects. Gap-link elements provide no resistance in tension. Only compressive forces activate elastic resistance in the element. The compressive sti ness is de ned to be arbitrarily large in order to capture the semi-rigid sti ness of the concrete oor slab. Figure II.9 shows a schematic of the gap-link element from SAP2000 [25]. Gap-links are geometrically arranged in order to approximate continuous elastic foundation conditions without causing convergence problems during analysis. Too many or too closely spaced nonlinear elements cause instability in the analysis solution, unless a su ciently small integration time step is used. Figure II.10a shows the decoupled model with gap-links attached to the bottom ange shell elements. Figure II.10b shows only the bottom ange with gap-links attached.
5. Assign time history joint loads from the post-processing of the previous GIS-building analysis to the nodes disconnected from the GIS-building model. See Figure II.10b for the nodes that are assigned the time history joint loads. The disconnected nodes previously joined the horizontal circuit breaker elements to the vertical current transformer elements. In the complete linear GIS-Building analysis, the current transformers acted as beam-columns transferring force to the circuit breakers below. The forces transferred to the circuit breakers take the form of time-varying loads in all six degrees of freedom. Six vertical current transformers transferred time-varying loads to six nodes in the circuit breakers. Therefore, thirty-six individual time-varying loads are assigned to the load-receiving nodes in the decoupled nonlinear model.

The purpose of the aforementioned process is to accurately capture the forces applied to the circuit breaker assembly resulting from the previous time-history quali cation analysis of the complete GIS-Building FE model.

Figure II.8: Governing CB Support Assembly from GIS-building Analysis

Figure II.9: Gap-Link Element Schematic

II.7 Nonlinear Time History Analysis Results

Anchor bolt shear and pull-out design forces for the circuit breaker (CB) support structure are determined from nonlinear time history nite element (FE) analysis of the decoupled

(a) Decoupled model nodal time history loads

(b) View of bottom anges and gap-links

Figure II.10: Decoupled Nonlinear Model of CB Supports

model and IEEE-693 (2005)[20] LRFD load combinations Equation (II.1). Design loads are checked according to standard ACI 318-14[26] using Hilti PROFIS Anchor 2.7.8 software [27]. Figure II.11 shows the typical CB support anchor bolt locations as displayed in both the computer-aided design (CAD) rendering of the design and the pinned support of the decoupled FE model. The following LRFD load combinations Equation (II.1) are used to determine the design loads for the anchor bolts.

$$1.2D + 1.4E \tag{II.1a}$$

$$0.9D + 1.4E \tag{II.1b}$$

Figure II.11: Circuit Breaker Anchor Bolt Locations

II.7.1 Circuit Breaker Anchor Bolt Design Loads

Circuit breaker anchor bolt design loads for both shear and pull-out forces are listed in Table II.1. In order to illustrate the e ect of the nonlinear gap-link elements, design loads are determined for two cases: bottom ange support without gap and with gap-links. The presence of gap-links help to simulate the e ect of the semi-rigid elastic foundation provided by the physical concrete oor slab. Note that the use of gap-link elements reduces anchor bolt pull-out and shear forces by about 20% and 40%, respectively. Circuit breaker anchor bolt design loads as determined by nonlinear time history analysis satisfy ACI-318 [26] design criteria and pass strength checks.

Table II.1: CB Anchor Bolt Forces (Maximum Envelope Forces)

Condition	Vx (kN)	Vy (kN)	N (kN)
wihout gap-links	38.8	13.9	50.2
with gap-links	31.2	14.5	32.7

II.8 Conclusions

Seismic quali cation of switchgear equipment by linear nite element time history analysis is insu cient to model and generate design loads for switchgear mounting

supports exhibiting geometric nonlinearities. This chapter explores the case study of seismic quali cation of an actual 230kV ELK14 GIS circuit breaker support anchor bolt arrangement exhibiting geometric nonlinear behavior. The procedure outlined in this chapter shows the necessity and practicality of performing nonlinear analysis on critical nonlinear support elements within the broader framework of seismic quali cation of the full equipment assembly.

CHAPTER III

E ect of Nonlinear Mounting Arrangement on High Frequency Response of In-Cabinet Response Spectrum

III.1 Introduction

Safety-related instruments in nuclear power plants, such as relays mounted within electrical cabinets, must be seismically quali ed to ensure functionality during and after an earthquake. Figure III.1 shows a picture of a typical electrical cabinet. The most commonly used methods for seismic quali cation are based on testing, analysis, a combination of testing and analysis, and/or experience data [28]. Seismic quali cation of electrical devices mounted within the cabinets is conducted by testing the devices on a shake table. The input motion for shake table testing is de ned as a generalized test response spectrum (TRS) that is broad banded in its frequency content in order to satisfy a wide range of possibilities because a given device can be mounted in multiple cabinet types and in di erent facilities. Designers and engineers of nuclear facilities generate plant speci c in-cabinet response spectrum (ICRS) curves, which is the acceleration response spectrum at a location in the cabinet (ideally at the device location). If the spectral accelerations in the ICRS are less than those in the TRS, in the complete frequency region of interest, then the devices are considered to be seismically quali ed. The ICRS is generated by analytical methods, by simpli ed ampli cation factors, or by shake table tests of the entire cabinet assembly [28 30]. Many studies have been conducted on understanding the dynamic behavior of cabinets and on developing methods for generating ICRS [31 35].

A large number of studies use the nite element method for analysis of cabinets. In almost all such studies, the cabinet nite element analysis models consider the cabinet to be rigidly anchored at the base, and the base is modeled as xed to the oor. However, the validity of a xed based assumption depends on the speci c mounting arrangement of the cabinet. Studies have shown that the exibility of the cabinet mounting arrangement can signi cantly a ect the cabinet dynamic behavior [8 11].

The flexibility of a mounting arrangement depends on the nature of mounting, such as anchoring or welding, as well as on the structural details specific to a given design. Both testing and analysis have been used to evaluate the effects of mounting arrangements on the dynamic properties of electrical cabinets. Llambias et al. [8] show that modeling of structural details at the cabinet base can be significant for response evaluation. Through shake table experiments, Llambias et al. [8] show that nonlinear yielding of supports at the bottom corners of cabinets can result in a reduction of stiffness at the base. Lee et al. [9] use both simple and detailed analytical approaches to evaluate the effect of base shimming on the seismic response of cabinets. According to Lee et al. [9], the cabinet base supports in an actual plant are often discontinuous due to the addition of shim plates. In contrast, the mounting arrangement for shake table testing in most cases employs continuous support conditions. As a result, the effective stiffness of the same structural support members can be much higher for shake table tests than for in-situ conditions [9]. Gupta and Yang [32] explore in detail the rigid body rocking of cabinets. They facilitate the incorporation of cabinet rocking modes in the Ritz vector approach by developing formulations to evaluate rocking stiffness for different mounting arrangements. Rustogi and Gupta [33] validate cabinet finite element analysis as well as the basis for the Ritz vector approach by using modal data obtained from in-situ and shake table tests of cabinets.

Other studies have explored the relationship between impact and nonlinear structural or equipment response. Herve et al. [35] studies the propagation of high-frequency ground motions in a structure, mainly caused by an aircraft impact. They propose a method to model and analyze a nonlinear elastic system based on experimental findings of Vlaski et al. [36], who study how high frequency motions caused by impacts from external hazards tend to filter out before reaching the equipment mounted in a cabinet. However, Herve et al. [35] only define methods used to evaluate floor response spectra and do not discuss the response of cabinets and relays. Lee and

Abou-Jaoude [10] consider the e ect of uplift on equipment response using a simpli ed analytical procedure in which the cabinet is modeled as an idealized SDOF system joined to a massless rigid base and supported on both edges by parallel springs that are rigid in compression but exible in tension. Lee and Abou-Jaoude [10] compare the dynamic response of their uplift model to xed base behavior. Their results show that spectral accelerations for uplift behavior are sometimes greater than for xed base behavior. However, their model does not capture the high frequency spectral responses for uplift behavior, as is explored later in this chapter.

Overall, the nonlinear behavior at the base of electrical cabinets can be categorized in terms of: (1) sliding due to base plate openings around anchor bolts and (2) rocking of the cabinet due to base plate uplift caused by overturning moments. Both sliding and rocking behavior results in an impact of the cabinet base with the anchor bolts or the oor supporting it. The existing studies that consider nonlinearities at the cabinet base do not consider the e ect of such localized impacts. Localized impacts can introduce high frequency vibrations in the cabinet. Historically, nuclear power plants have been designed for only low frequency earthquakes, and the e ect of high frequency vibrations have not been considered. In recent years, seismological studies have identi ed that the earthquake ground motions at many nuclear power plant sites in the United States and in other countries contain high frequency content [37]. In addition, it has also been observed that the continued functionality of electrical devices, such as relays and switches, is vulnerable to high frequency vibrations [38].

In this chapter, an exploratory study is presented that considers the e ects of nonlinear mounting conditions on the dynamic response of cabinets. Two di erent simpli ed representations are considered in this study to understand and explain the e ect of such impacts induced by nonlinear mounting conditions:

1. Sliding behavior of a single degree of freedom (SDOF) representation of a cabinet

subjected to harmonic base excitation.

2. Rocking behavior due to base uplift in a multi degree of freedom (MDOF) representation of a cabinet subjected to seismic excitation.

In both cases, it is observed that ICRS generated by considering the e ects of impacts due to nonlinearities exhibit secondary peaks in the high frequency region. These secondary high frequency response peaks in the ICRS occur at a periodicity that is a function of the fundamental natural frequency of the system. Such secondary peaks are not present in the corresponding xed base model approaches. This study concludes that if such secondary peaks are ignored in the generation of ICRS, the seismic quali cation of electrical devices can be adversely a ected. ICRS generated by a xed base model or any model that ignores the e ect of nonlinear impacts, even if base exibility is considered, can underestimate the spectral accelerations in high frequency regions. Consequently, electrical devices may not be appropriately quali ed.

Figure III.1: Electrical Cabinet Equipment

III.2 Sliding Response of SDOF System

III.2.1 Description of SDOF System with Nonlinear Base

Figure III.2 shows the SDOF oscillator considered in this study with what can be considered as a stationary base that is periodically excited by an oscillating ground surface. The oscillating ground comes in and out of contact with the base of the SDOF system as the gap between them closes and opens repeatedly. When the ground is in contact with the base, the base moves with the ground, subjecting the system to xed base SDOF excitation (closed gap condition). When the oscillating ground surface is not in contact with the base, the base remains in a xed position (open gap condition), and the SDOF system undergoes free vibration until the ground surface once again comes back into contact with the base. The oscillator has a horizontal translational DOF u at the lumped mass m. A linear spring element of sti ness k and a linear dashpot element of damping constant c join the oscillating mass to the base. The maximum gap distance is denoted by d_{gap}.

Figure III.2: SDOF System with Nonlinear Contact Condition

III.2.2 Equations of Motion

The governing equations of motion for the nonlinear SDOF system Figure III.2 and the associated contact conditions, open-gap free vibration and closed-gap forced excitation, as well as the transition criteria between the contact conditions, are presented below.

1. Open-Gap Free Vibration

   When the base and oscillating ground surface are not in contact, the motion of the SDOF system is governed by the standard di erential equation for free vibration Equation (III.1).

$$m\ddot{u} + c\dot{u} + ku = 0 \qquad \text{(III.1)}$$

   The initial conditions of the system are the relative displacement and velocity of the oscillating mass at the instance of initiation of free vibration.

2. Closed-Gap Forced Excitation

   When the base and oscillating ground surface are in contact, the motion of the SDOF system is governed by the standard di erential equation for xed base excitation Equation (III.2).

$$m\ddot{u} + c\dot{u} + ku = m\ddot{u}_g(t) \qquad \text{(III.2)}$$

   In this study, the ground motion $\ddot{u}_g(t)$ is considered to be a harmonic sinusoidal motion in order to understand and explain the outcome using a closed-form theoretical solution. The harmonic ground acceleration is shown in Equation (III.3).

$$\ddot{u}_g(t) = A_0 \sin(\ \ t) \qquad \text{(III.3)}$$

   A_0 is the amplitude of ground acceleration and is the ground motion excitation

circular frequency. The time period of excitation can be written as shown in Equation (III.4).

$$T = \frac{2}{} \qquad \text{(III.4)}$$

The displacement amplitude can be obtained from Equation (III.3) as shown in Equation (III.5).

$$G_0 = \frac{A_0}{2} \qquad \text{(III.5)}$$

The initial conditions of the system are the relative displacement and velocity of the oscillating mass at the instance of initiation of base excitation.

3. Transition State: Initiation of Base Excitation

The system is subjected to a harmonic base excitation Equation (III.3) when the gap between the base and oscillating ground surface is closed. This case study assumes that the initial location of the oscillator base before excitation is the geometric middle of the gap distance d_{gap}. The exact times at which the base makes contact with the ground surface can be determined analytically. Initial contact occurs at time $t^{initial}_{gap\ closed}$ when the ground displaces a total distance of $d_{gap}/2$, as shown in Equation (III.6).

$$t^{initial}_{gap\ closed} = \frac{1}{2}\arcsin\left(\frac{d_{gap}}{2}\frac{1}{G_0}\right)T \qquad \text{(III.6)}$$

4. Transition State: Intervals of Free Vibration

The system undergoes free vibration after the gap opens and as the oscillating ground surface loses contact with the system base. These intervals of free vibration begin when the ground acceleration Equation (III.3) reaches a maxima at time $t^{maxima}_{gap\ open}$ or minima at time $t^{minima}_{gap\ open}$ as shown in Equation (III.7).

$$t^{maxima}_{gap\ open} = (\frac{1}{4} + n_p)T \qquad \text{(III.7a)}$$

$$t^{minima}_{gap\ open} = (\frac{3}{4} + n_p)T \qquad \text{(III.7b)}$$

The variable n_p denotes the number of completed ground oscillation periods, beginning at $n_p = 0$ and continuing with n_p=1, 2, 3,. . . , etc.

5. Transition State: Intervals of Base Excitation

The system undergoes harmonic base excitation when the gap is closed and the oscillating ground surface makes contact with the system base. This interval of base excitation occurs after the ground displaces a total distance of d_{gap} after the onset of free vibration. The time required for the ground to displace a total distance of d_{gap} is determined by Equation (III.8).

$$= \frac{1}{2}\arcsin(\ 1 + \frac{d_{gap}}{G_0})T + \frac{1}{4}T \qquad \text{(III.8)}$$

Therefore, the interval of base excitation begins after a span of time following the time of maximum or minimum ground acceleration Equation (III.3), can be expressed as shown in Equation (III.9).

$$t^{maxima}_{gap\ closed} = (\frac{1}{4} + n_p)T + \qquad \text{(III.9a)}$$

$$t^{minima}_{gap\ closed} = (\frac{3}{4} + n_p)T + \qquad \text{(III.9b)}$$

III.2.3 Evaluation of Ampli cations

To study the e ect of localized impacts in the mounting arrangement, variations in the transmissibility ratio, TR, of the SDOF systems are evaluated and studied. The transmissibility ratio is the ratio of maximum total (absolute) acceleration of the SDOF system to the maximum ground acceleration, as shown in Equation (III.10).

$$TR = \frac{\ddot{u}_{Total}^{max}}{A_0} \qquad \text{(III.10)}$$

At any instance of time, the total response of the system $\ddot{u}_{total}$ is the summation of the relative transient response $\ddot{u}_{tr}$, the relative steady-state response $\ddot{u}_{ss}$, and the instantaneous base excitation $\ddot{u}_g$. The total absolute acceleration can then be expressed as shown in Equation (III.11).

$$\ddot{u}_{total} = \ddot{u}_{tr} + \ddot{u}_{ss} + \ddot{u}_g \qquad \text{(III.11)}$$

Note that when the nonlinear SDOF is subjected to free vibration, Equation (III.1) is the governing equation of motion and $\ddot{u}_g$ is zero. When the system is subjected to harmonic base excitation, Equation (III.2) is the governing equation of motion, and $\ddot{u}_g$ is given by Equation (III.3).

III.2.4 Application Case Study

A suite of SDOF systems are studied by varying three di erent parameters in order to understand their e ect on the in-cabinet ampli cations, i.e., the transmissibility ratio Equation (III.10). The three parameters considered are:

1. natural frequency of the SDOF system ω_n,
2. frequency of harmonic ground excitation,
3. the maximum gap distance between the base and the oscillating ground surface, d_{gap}

The rst two of these parameters determine the frequency ratio, which in turn governs the resonance condition. The third d_{gap}, a ects the nature and the number of impacts in the base. A smaller value of the maximum gap distance would result in more

frequent impacts, whereas a larger value would result in less frequent impacts. On the other hand, a larger gap can also mean greater velocity at the time of impact.

Figure III.3 shows the transmissibility ratio curves for a suite of such SDOF systems as evaluated in accordance with Equation (III.1) to Equation (III.11) for 2% damping. The harmonic ground motion has an excitation frequency of $= 5$ Hz and an acceleration amplitude of $A_0 = 10\frac{m}{s^2}$. Each curve corresponds to di erent values of maximum gap distance d_{gap}. The No Gap curve represents linear systems supported by the conventional xed base condition with no intervals of free vibration.

Figure III.3: Transmissibility Ratio Curves (2% Damping) for 5Hz Sinewave Base Excitation of SDOF System with Nonlinear Contact Condition.

Transmissibility plots in Figure III.3 reveal a key observation: the curves for 1mm and 8mm Gap exhibit multiple peaks in the high frequency region in addition to the peak at 5 Hz. The peak at 5 Hz corresponds to a frequency ratio of unity. However, all the subsequent peaks occur at much smaller values of frequency ratio. The di erences

between the fixed base (No Gap) curve and the nonzero gap curves are quite large for oscillators of high frequencies. Table III.1 compares the numeric values of transmissibility ratios (TR) at specific frequencies of peaks and troughs for the No Gap and 1mm Gap cases. Note that the nonlinear 1mm Gap curve response can be four to five times greater than the linear No Gap curve in the high frequency region. The accelerations in systems with higher frequencies can be much larger if a gap condition is considered when compared to a fixed base analysis. This observation emphasizes that in real systems, the ICRS used for seismic qualification may be underestimated if nonlinearities at the cabinet base are not considered.

Another key observation in Figure III.3 relates to the frequencies at which the peaks and troughs occur for the cases with base nonlinearities. The peaks occur approximately at odd multiples of the excitation frequency, while the troughs occur approximately at even multiples of the excitation frequency. More specifically, the nonzero gap curves exhibit response peaks at approximately $\omega = 5\text{Hz}$, $\omega = 15\text{Hz}$, $\omega = 25\text{Hz}$, etc. and troughs at approximately $\omega = 10\text{Hz}$, $\omega = 20\text{Hz}$, $\omega = 30\text{Hz}$, etc. A detailed discussion on the reasons for the occurrence of these high frequency secondary peaks and troughs at periodic intervals is presented in the following section.

Table III.1: Transmissibility Ratio Comparison for Linear vs Nonlinear SDOF System

Oscillator Key Frequency		Freq. Ratio (Excitation/ Oscillator)	Transmissibility Ratio Values		Ratio of TR Responses (Nonlinear vs Linear)
Descr.	Value (Hz)		No Gap	1mm Gap	
Peak	5.0	1.00	23.9	17.5	0.732
Trough	9.5	0.53	1.86	1.41	0.761
Peak	15.0	0.33	1.47	7.01	4.78
Trough	21.5	0.23	1.22	1.88	1.54
Peak	25.1	0.20	1.06	6.30	5.94

III.2.5 Discussion

In this section, details of the time varying response for the nonlinear SDOF system Figure III.2 are presented in order to explain the reasons for the high frequency secondary response peaks observed in Figure III.3. To begin with, a comparison is made between the root mean square (RMS) of the acceleration responses for linear (No Gap) and nonlinear systems over an excitation time-span of 5.0 seconds. The RMS is a useful time independent measure of the strength of a harmonic function that can be used to compare the relative contributions that the steady-state and transient components make to the total response of the system over the given excitation duration. Table III.2 shows how the RMS of steady-state response for both the No Gap and 1mm Gap oscillator frequencies are similar. However, the RMS of the transient responses for the 1mm Gap condition are signi cantly greater than the No Gap condition. The transients for the 1mm Gap system vary in intensity in accordance with oscillator natural frequencies depending upon an even multiple (peaks) or an odd multiple (troughs) of the input motion frequency .

Table III.2: Acceleration Time History RMS Comparison for Linear vs. Nonlinear SDOF Systems

Oscillator Key Frequency		Freq. Ratio (Excitation/ Oscillator)	Root Mean Square of Acceleration Response (m/s^2)			
			No Gap		1mm Gap	
Descr.	Value (Hz)		Transient	Steady-State	Transient	Steady-State
Peak	5.0	1.00	70.5	177	93.4	175
Trough	9.5	0.53	1.49	2.71	5.31	2.31
Peak	15.0	0.33	0.611	0.884	41.4	0.755
Trough	21.5	0.23	0.334	0.404	6.92	0.346
Peak	25.1	0.20	0.261	0.292	37.1	0.250

The high frequency response peaks arise from the transient motions that are produced when the nonlinear SDOF system subjected to harmonic base excitation undergoes transitions between states of excitation. For frequency ratios much less than 1

(high frequency oscillators), the transient motion is relatively much greater than the steady state response of the system during forced excitation. The repeated transitions do not allow the transient response of the nonlinear system to damp out but rather contribute to an increase in the total response of the system. In contrast, a linear xed base SDOF system with a frequency ratio much less than 1 acts rigidly and produces negligible response from steady state as well as transient motions. The total acceleration in such a linear system is mostly comprised of the acceleration from base excitation. This phenomenon can be illustrated by examining the acceleration time series for various responses. Figure III.4 shows a snapshot of the time varying acceleration responses for an SDOF system with the following parameters = 5 Hz, ! = 15Hz, and d_{gap} = 0mm, which represents a linear xed base condition with a frequency ratio of 0.33. Figure III.5 shows the acceleration responses for nonlinear sliding behavior of the same system such that = 5 Hz, ! = 15Hz, and d_{gap} = 1mm. The plots display the total response, steady-state response, transient response, and base excitation motion of the systems. The plot limits are restricted to one period of the base excitation motion at an arbitrary time interval.

The harmonic motions that contribute to the total acceleration response of the systems are notably dissimilar between Figure III.4 and Figure III.5, despite both systems possessing the same ratio of forcing frequency to natural frequency. For the linear xed base case shown in Figure III.4, the transient response has damped out to zero and the steady-state response amplitude is also very small due to the low value of The total response in Figure III.4 is dominated by the instantaneous base excitation. However, for the nonlinear 1mm Gap case, the acceleration response shown in Figure III.5 exhibits signi cantly di erent behavior. The transient response does not damp out but instead ampli es and is the largest contributor to the total response of the system. The steady-state response and the instantaneous base excitation alternate between zero and nonzero during the continuously transitioning states of vibration. Figure III.5 visually illustrates

Figure III.4: Acceleration Time History for Linear SDOF System (Forcing Frequency: = 5 Hz, Natural Frequency:! = 15Hz, Gap Distance:d_{gap} = 0mm)

the signi cance of localized impact due to nonlinearity at the base, which introduces transient motions and thereby increases the total system response. Consequently, the impacts result in the high frequency peaks as shown in Figure III.3. However, whether or not the transient motion results in a peak or trough in the response of the nonlinear system depends on the phase di erence at each frequency ratio.

Analysis of the nonlinear sliding SDOF systems (Figure III.2) shows that transient motions that peak in accordance with constructive wave interference between

Figure III.5: Acceleration Time History for Nonlinear SDOF System (Forcing Frequency: $= 5\ \mathrm{Hz}$, Natural Frequency: $! = 15\mathrm{Hz}$, Gap Distance: $d_{gap} = 1\,\mathrm{mm}$)

the excitation and natural vibrations dominate the total response (Figure III.5). In general, any two harmonic functions that oscillate at frequencies that are odd multiples of each other will exhibit in-phase motion such that the maxima and minima occur at the same time instant twice within any given period, resulting in constructive interference of the waveforms. Such constructive interference results in a peak response, as seen in Figure III.3. Harmonic functions that oscillate at frequencies that are even multiples of each other will exhibit out-of-phase motion such that the maxima and

minima do not occur at the same time instant within any given period, resulting in destructive interference of the waveforms. Such destructive interference results in a trough, as seen in Figure III.3. The peaks and troughs in Figure III.3 no not always occur at exact integer multiples because the steady-state response, although relatively much smaller than the transient response, can still interfere with phase alignment of the transient and base excitation motions.

Damping and the physical geometry of the system also play a complex role in the shape of the high frequency secondary peaks seen in Figure III.3. For the high frequency peaks in Figure III.3, the 8mm Gap responses are less than the 1mm Gap because systems with larger gaps will experience fewer impacts during any given span of time, so not enough transient motions can form fast enough before damping diminishes them. However, the rst secondary high frequency peak at $f = 10Hz$ for the 8mm Gap is greater than the 1mm Gap because the e ect of damping is lower than for higher frequencies and the larger gap allows for more time for the transient motions to form and coalesce.

III.3 Rocking Behavior in MDOF System

This section presents the description and results from the study of a simpli ed cabinet model exhibiting nonlinear uplift and rocking behavior when subjected to seismic base excitation. The nonlinear contact behavior of the system generates an ICRS with a pattern of high frequency response peaks due to localized impacts. The study presented in this section compares the responses for the nonlinear system with those for two corresponding linear systems: linear xed base and linear exible base models.

III.3.1 Description of MDOF System with Nonlinear Base

Figure III.6 shows the MDOF system used to represent a simpli ed cabinet model exhibiting nonlinear uplift and rocking behavior when subjected to seismic base excitation. As shown in Figure III.6, the cabinet is modeled as a structural frame

element of height h joined to a massless rigid base of width $2b$. This system is supported on both edges by parallel vertical nonlinear springs that are rigid in compression but flexible in tension, hence allowing for nonlinear rocking and uplift of the base under dynamic loads. The total mass of the cabinet is m, and the acceleration due to gravity is g.

Figure III.6: Simple Representation of Cabinet Model: Absence of Uplift (Equivalent to Linear Fixed Base Approach)

When subjected to seismic base excitation, the nonlinear model transitions between two contact conditions: absence of uplift (Figure III.6) and presence of uplift about either edge (Figure III.7). In the absence of uplift, the base acts as a fixed restraint and the system behaves as a MDOF oscillator (Figure III.6) with horizontal translational DOF u and rotational DOF θ at the top of the cabinet. However, the system will experience uplift (Figure III.7) if the overturning moment about edges O or O^0 caused by inertial effects exceeds the restoring moment due to gravitational loads. To consider uplift, nonlinear

springs are considered at both ends of the cabinet base. These springs have in nite sti ness in compression but a nite sti ness of k_s in tension. Uplift deformation is characterized by three degrees of freedom: horizontal translational DOF u and rotational DOF $_1$ at the top of the cabinet and rigid body rotation $_2$ at the base. The equipment anchor bolts prevent horizontal translation at the base. The model presented in this report represents the structural cabinet body as a frame element with exural rigidity EI. The mass distribution is not lumped but is applied using the consistent mass method, i.e., the nodal mass assignments are consistent with the shape functions used to derive the frame element sti ness properties. Consistent mass matrix formulation provides theoretically accurate dynamic analysis results and signi cantly e ects the rocking response, as discussed later in the results section. For visual simplicity, mass distribution for Figure III.6, Figure III.7, and Figure III.8 is generalized by the variable m.

Figure III.7: Cabinet Model: Base Uplift About One Edge

The study presented in this chapter compares the ICRS generated by three di erent methods: (1) linear xed base, (2) linear rotational spring at base, (3) nonlinear base uplift.

Figure III.8: Cabinet Model: Linear Rotational Spring (Flexible Base)

The two linear analyses considered correspond to the xed base approach (Figure III.6) and the rotational spring model (Figure III.8), respectively. The linear xed base method (Figure III.6) is equivalent to the nonlinear base uplift model but with the complete absence of uplift. The linear rotational spring model (Figure III.8) lumps the rotational sti ness of the cabinet base into a single spring element of sti ness k_s and is characterized by three degrees of freedom: horizontal translational DOF $\bar{u}$ and rotational DOF $_1$ at the top of the cabinet and rigid body rotation $_2$ at the base.

III.3.2 Equations of Motion

The equations of motion for the nonlinear base uplift model (Figure III.6 and Figure III.7) corresponding to the two contact conditions, absence of uplift and presence of uplift, as well as the transition criteria for the two contact conditions, are presented below. The vertical reactions at either edge of the cabinet base, $R_{O^0}(t)$ and $R_O(t)$, determine the

presence or absence of uplift at any given instant of time. Upward vertical reactions are taken as positive. The displacements are assumed to be small, and second order P-Delta e ects are neglected.

1. Absence of Uplift (Equivalent to Fixed Base)

   When both edges of the base remain in compressive contact with the oor, the system acts as a xed base MDOF oscillator with horizontal translational DOF u and rotational DOF at the top of the cabinet (Figure III.6). The equation of motion is derived by assembling the frame element mass and sti ness properties and directly eliminating the restrained degrees of freedom. The mass distribution is determined using the consistent mass formulation. The damping matrix is determined by Rayleigh damping whereby the rst two fundamental modes of vibration are set to a constant damping ratio of . The equation of motion can be written as shown in Equation (III.12)a. Equation (III.12)b is the displacement vector, Equation (III.12)c is the consistent mass matrix, Equation (III.12)d is the sti ness matrix, Equation (III.12)e is the nodal load vector.

$$[M]\{\ddot{U}(t)\} + [C]\{\dot{U}(t)\} + [K]\{U(t)\} = \{F(t)\} \qquad \text{(III.12a)}$$

$$\{U(t)\} = \begin{Bmatrix} u(t) \\ (t) \end{Bmatrix} \qquad \text{(III.12b)}$$

$$[M] = \begin{bmatrix} \frac{13}{35}m & \frac{11}{210}mh \\ \frac{11}{210}mh & \frac{1}{105}mh^2 \end{bmatrix} \qquad \text{(III.12c)}$$

$$[K] = \begin{bmatrix} \frac{12EI}{h^3} & \frac{6EI}{h^2} \\ \frac{6EI}{h^2} & \frac{4EI}{h} \end{bmatrix} \qquad \text{(III.12d)}$$

$$\{F(t)\} = [M]\begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \ddot{u}_g(t) \qquad \text{(III.12e)}$$

The vertical base reaction forces for the absence of uplift contact condition are expressed in Equation (III.13) and Equation (III.14).

$$R_{O^0}(t) = \frac{1}{2}mg \quad \frac{3EI}{bh^2}u(t) \quad \frac{EI}{bh}\ (t) \qquad \text{(III.13)}$$

$$R_O(t) = \frac{1}{2}mg + \frac{3EI}{bh^2}u(t) + \frac{EI}{bh}\ (t) \qquad \text{(III.14)}$$

2. Presence of Uplift

When one edge of the base uplifts, the corresponding spring activates in tension (Figure III.7). The system behaves as a MDOF system with degrees of freedom being horizontal translation DOF u and rotational DOF $_1$ at the top of the cabinet and rigid body rotation $_2$ at the base. The equation of motion is derived by assembling frame, spring, and rigid link elements and by eliminating the restrained degrees of freedom. The mass distribution is determined using the consistent mass formulation. The damping matrix is determined by Rayleigh damping whereby the rst two fundamental modes of vibration are set to a constant damping ratio of . The equation of motion can be written as shown in Equation (III.15)a. Equation (III.15)b is the displacement vector, Equation (III.15)c is the consistent mass matrix, Equation (III.15)d is the sti ness matrix, Equation (III.15)e is the total nodal load vector. Equation (III.15)f is the e ective nodal load vector from base excitation, Equation (III.15)g is the dead load vector for uplift about edge O^0, and Equation (III.15)h is the dead load vector for uplift about edge O.

$$[M]\{\ddot{U}(t)\} + [C]\{\dot{U}(t)\} + [K]\{U(t)\} = \{F(t)\} \qquad \text{(III.15a)}$$

$$\{U(t)\} = \begin{Bmatrix} u(t) \\ \theta_1(t) \\ \theta_2(t) \end{Bmatrix} \tag{III.15b}$$

$$[M] = \begin{bmatrix} \frac{13}{35}m & \frac{11}{210}mh & \frac{13}{420}mh \\ \frac{11}{210}mh & \frac{1}{105}mh^2 & \frac{1}{140}mh^2 \\ \frac{13}{420}mh & \frac{1}{140}mh^2 & \frac{1}{105}mh^2 + mb^2 \end{bmatrix} \tag{III.15c}$$

$$[K] = \begin{bmatrix} \frac{12EI}{h^3} & \frac{6EI}{h^2} & \frac{6EI}{h^2} \\ \frac{6EI}{h^2} & \frac{4EI}{h} & \frac{2EI}{h} \\ \frac{6EI}{h^2} & \frac{2EI}{h} & 4k_s b^2 + \frac{4EI}{h} \end{bmatrix} \tag{III.15d}$$

$$\{F(t)\} = \{F_{EQ}(t)\} + \{F_{DL}\} \tag{III.15e}$$

$$\{F_{EQ}(t)\} = [M] \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix} \ddot{u}_g(t) \tag{III.15f}$$

$$\{F_{DL}\} = \begin{Bmatrix} 0 \\ 0 \\ mgb \end{Bmatrix} \tag{III.15g}$$

$$\{F_{DL}\} = \begin{Bmatrix} 0 \\ 0 \\ mgb \end{Bmatrix} \tag{III.15h}$$

The vertical base reaction forces for the presence of uplift contact condition about edge O^0 are shown in Equation (III.16) and Equation (III.17).

$$R_{O^0}(t) = 2bk_s\ _2(t) \qquad \text{(III.16)}$$

$$R_O(t) = \quad 2bk_s\ _2(t) + mg \qquad \text{(III.17)}$$

The vertical base reaction forces for the presence of uplift contact condition about edgeO are shown in Equation (III.18) and Equation (III.19).

$$R_{O^0}(t) = 2bk_s\ _2(t) + mg \qquad \text{(III.18)}$$

$$R_O(t) = \quad 2bk_s\ _2(t) \qquad \text{(III.19)}$$

3. Initiation of Uplift at Base Edge

The system experiences uplift if the overturning moment about edge O or O^0 caused by inertial e ects exceeds the restoring moment caused by gravitational loads. During analysis, the uplift condition is identi ed by the vector direction of the two vertical reaction forces, $R_{O^0}(t)$ and $R_O(t)$, acting at each edge of the base of the equipment. In the absence of uplift, both vertical reaction forces act upwards. Uplift is initiated when either reaction changes sign and acts downward, which is summarized by the following conditions:

- if $R_{O^0} < 0$ and $R_O \quad 0$, then uplift about edge O^0 is initiated
- if $R_{O^0} \quad 0$ and $R_O < 0$, then uplift about edge O is initiated

4. Re-establish Contact After Uplift

When the uplifted edge makes contact again with the ground, an impact occurs. This impact is modeled as a perfectly inelastic collision. There is no rebound of the base upon impact. The vertical and rotational velocity are completely dissipated upon establishing contact. The onset of contact is identi ed by the direction of

the vertical reaction force acting at the corresponding edge of the equipment base, which is summarized by the following conditions:

- after uplift about edge O^0, if R_{O^0} 0, then contact is re-established
- after uplift about edge O, if R_O 0, then contact is re-established

5. Equations of Motion for Linear Rotational Spring Model

The cabinet can also be modeled with a linear exible base. The system behaves as a MDOF system with degrees of freedom being horizontal translation DOF u and rotational DOF $_1$ at the top of the cabinet and rotational DOF $_2$ at the base. The equation of motion is derived by assembling frame and spring elements and by eliminating the restrained degrees of freedom. The mass distribution is determined using the consistent mass formulation. The damping matrix is determined by Rayleigh damping whereby the rst two fundamental modes of vibration are set to a constant damping ratio of . The equation of motion can be written as shown in Equation (III.20)a. Equation (III.20)b is the displacement vector, Equation (III.20)c is the consistent mass matrix, Equation (III.20)d is the sti ness matrix, and Equation (III.20)e is the nodal load vector.

$$[M]\{\ddot{U}(t)\} + [C]\{\dot{U}(t)\} + [K]\{U(t)\} = \{F(t)\} \qquad \text{(III.20a)}$$

$$\{U(t)\} = \begin{Bmatrix} u(t) \\ {}_1(t) \\ {}_2(t) \end{Bmatrix} \qquad \text{(III.20b)}$$

$$[M] = \begin{bmatrix} \frac{13}{35}m & \frac{11}{210}mh & \frac{13}{420}mh \\ \frac{11}{210}mh & \frac{1}{105}mh^2 & \frac{1}{140}mh^2 \\ \frac{13}{420}mh & \frac{1}{140}mh^2 & \frac{1}{105}mh^2 \end{bmatrix} \qquad \text{(III.20c)}$$

$$[K] = \begin{bmatrix} \frac{12EI}{h^3} & \frac{6EI}{h^2} & \frac{6EI}{h^2} \\ \frac{6EI}{h^2} & \frac{4EI}{h} & \frac{2EI}{h} \\ \frac{6EI}{h^2} & \frac{2EI}{h} & k_r + \frac{4EI}{h} \end{bmatrix} \tag{III.20d}$$

$$\{F(t)\} = [M] \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix} \ddot{u}_g(t) \tag{III.20e}$$

III.3.3 Application Case Study

When subjected to seismic base excitation, the nonlinear base uplift cabinet model transitions between two contact conditions: absence of uplift (Figure III.6) and presence of uplift about either edge (Figure III.7). For seismic base excitation, time stepping methods are implemented in order to solve the equations of motion and generate the ICRS. This study uses the Newmark-beta numerical scheme for constant average acceleration [39]. The primary response quantity of interest is the transmissibility ratio, TR. The transmissibility ratio is the ratio of the absolute acceleration response of a device located in the cabinet, $\ddot{u}^{total}_{device}$, to the input floor acceleration, as shown in Equation (III.21). PFA is the peak floor input acceleration. In essence, TR is representative of the ICRS and the terms are used interchangeably in the discussion that follows.

$$TR = \frac{\max(\ddot{u}^{total}_{device})}{PFA} \tag{III.21}$$

Numerical values for equipment properties and other system parameters are chosen in order to reasonably represent a typical cabinet. The system properties used for the numerical study in this chapter are summarized in Table III.3. The fundamental modal

frequencies of the three cabinet models considered are summarized in Table III.4.

Table III.3: System Properties for Cabinet Base Excitation Analysis

Cabinet Model Property	Symbol	Value	Units
cabinet height	h	2.0	meters
half cabinet base width	b	0.4	meters
total cabinet mass	m	5000	kilogram
gravity constant	g	10	m/s^2
exural rigidity	EI	1.15E+07	N*m^2
axial rigidity	AE	in nity	N
base uplift spring sti ness	k_s	5.25E+07	N/m
exible base spring sti ness	k_r	1.68E+07	N*m/rad
damping constant (1st and 2nd modes)		0.02	
peak oor acceleration	PFA	10	m/s^2

Table III.4: Modal Frequencies of Cabinet Finite Element Models

Cabinet Finite Element Model	Modal Frequencies (Hz) 1st Mode	2nd Mode	3rd Mode
Fixed Base	9.53	93.9	N/A
Base Uplift	7.24	37.5	103
Flexible Base	6.15	57.4	203

In this study, the ICRS at the translational DOF u of the nonlinear base uplift model (Figure III.6 and Figure III.7) is compared with the ICRS for the two linear approaches, i.e., xed base (Figure III.6) and rotational spring (Figure III.8). The input motion used for the time history analysis is the IEEE-6932[0] compatible x-direction Landers time history motion scaled to 1.0g4[0]. The seismic loads from the Landers motion are combined with the dead loads from the self-weight of the cabinet. Figure III.9 shows a plot of the transmissibility ratio (TR) curves generated using three di erent approaches as well as the TR curve for the oor supporting the base of the cabinet. The curve corresponding to nonlinear base uplift exhibits response peaks in the high frequency region. The corresponding linear models do not exhibit such high frequency response peaks.

III.3.4 Discussion

The nonlinear contact conditions play a signi cant role in the equipment response. Table III.5 tabulates and compares the TR's at key frequency values for the three di erent models. The nonlinear base uplift model response at the rst peak is approximately 30% to 50% smaller than the corresponding linear model responses. However, at higher frequencies, the nonlinear base uplift model exhibits additional response peaks that are signi cantly greater than the linear models: up to 5.24 and 5.04 times greater than the linear xed base and rotational spring approaches, respectively. Consideration of nonlinear contact conditions for rocking and uplift behavior produces signi cantly greater responses at high frequencies as compared to the linear methods. This is similar to the observation made for the nonlinear sliding SDOF system (Figure III.2) discussed earlier, except that for MDOF systems, all natural modes with su cient modal participation are also excited by the impact behavior. The linear models exhibit high ICRS response only in the fundamental mode, but the nonlinear base uplift model exhibits secondary peaks in the high frequency region.

Table III.5: Transmissibility Ratio Comparison for Linear vs. Nonlinear Cabinet Base Excitation

Base Uplift Transmissibility Ratio Peak Responses			Ratio of TR Responses (Nonlinear Base Uplift / Linear Systems)	
Descr.	Freq. (Hz)	TR Value	Uplift / Fixed Base	Uplift / Rot. Spring
1st Peak[a]	7.63	30.8	0.686	0.495
2nd Peak[b]	39.4	23.5	4.64	4.61
3rd Peak[b]	105	25.2	5.24	5.04

[a]Linear xed base and rot. spring responses are measured at their respective fundamental frequencies;
[b]No discernible peaks for linear models, so the linear xed base and rot. spring responses are measured at the corresponding base uplift model peak response frequencies

It is observed that modeling of the mass matrix for the cabinet also in uences the high frequency peaks. The mass matrices considered in Equation (III.12),

Figure III.9: Transmissibility Ratio Curves (2% Damping) for Cabinet Base Excitation: Linear Analysis vs. Nonlinear Analysis

Equation (III.15), and Equation (III.20) are obtained using the consistent mass approach. Use of consistent mass matrix is quite rare both in research and practice. In the case of nonlinear rocking behavior, the nature of the mass matrix can a ect the intensity of high frequency response peaks signi cantly, as shown in Figure III.10, which plots the TR curves for two cases of the nonlinear base uplift model: the consistent mass matrix and the lumped mass matrix formulation. The lumped mass approach exhibits much smaller TR responses and modal participation factors for modes at high frequencies than the consistent mass approach. Table III.6 tabulates the transmissibility ratio values for the two mass distributions, and Table III.7 compares the modal participation factors between the consistent and lumped mass formulations. At the rst

response peak, the consistent mass distribution response is about 37% less than the lumped mass distribution response because the consistent mass model exhibits lower modal participation for the rst mode. However, in the high frequency region, the consistent mass response for the second peak is 3.35 times greater than the lumped response. For the third response peak, the lumped mass peak is non-existent, and the consistent response is 6.44 times greater. The discrepancy between consistent and lumped mass in the high frequency region is due to the much higher modal participation for the high frequency consistent mass modes. Regardless of consistent or lumped mass matrix formulation, the nonlinear base uplift models exhibit larger responses in the high frequency region than the corresponding linear models due to the repeated excitation of transient vibrations induced by impacts from rocking behavior.

Figure III.10: Transmissibility Ratio Curves (2% Damping) for Cabinet Base Excitation: Consistent Mass Formulation vs. Lumped Mass Formulation

Table III.6: Transmissibility Ratio Comparison for Consistent Mass vs. Lumped Mass Cabinet Base Excitation

Base Uplift Model TR Peak	Transmissibility Ratio Values		Ratio of TR Responses (Consistent/Lumped)
	Consistent Mass	Lumped Mass	
1st Peak	30.8	48.5	0.635
2nd Peak	23.5	7.02	3.35
3rd Peak[a]	25.2	3.92	6.44

[a]No third peak for lumped mass response, so lumped mass response is measured at third peak of consistent mass response

Table III.7: Modal Participation Factor Comparison for Consistent Mass vs. Lumped Mass Models

Cabinet Finite Element Model	Ratio of Modal Participation Factors (Consistent/Lumped)		
	1st Mode	2nd Mode	3rd Mode
Absence of Uplift (Fixed Base)	0.855	739	N/A
Base Uplift	0.854	0.956	721

III.4 Summary and Conclusion

In this chapter, an exploratory study is presented to study the e ect of localized impacts on in-cabinet ampli cations due to nonlinear sliding and rocking at the cabinet base during base excitation. Two di erent representations are considered in this study:

1. Sliding behavior of a single degree of freedom (SDOF) representation of a cabinet subjected to harmonic base excitation.
2. Rocking behavior due to base uplift in a multi degree of freedom (MDOF) representation of a cabinet subjected to seismic excitation.

In both cases, it is observed that in-cabinet ampli cations generated by considering the e ects of impacts due to nonlinearities exhibit secondary peaks in the high frequency

region. These secondary, high frequency response peaks occur at a periodicity that is a function of the fundamental natural frequency of the system. Such secondary peaks are not present in the corresponding analyses of linear xed base and linear exible base models. The nonlinear gap conditions induce transient motions that are imparted by the opening and closing of the gaps. The transient motions do not damp out in such nonlinear systems due to repeated impacts. The transient motions produce peak responses in the high frequency region due to constructive wave interference between the transient motions and base excitation.

This study concludes that if such secondary peaks are ignored in the generation of ICRS, the seismic quali cation of electrical devices can be adversely a ected. ICRS generated by a xed base model or any model that ignores the e ect of localized nonlinearities, even when base exibility is considered, can underestimate the spectral accelerations in high frequency regions.

CHAPTER IV

BIM Interoperability Tool for Improving IFC-based Model Data Exchange Between Architectural Design and Structural Analysis for Building Structures

IV.1 Introduction

IV.1.1 The Demand for BIM Interoperability to Facilitate Structural Analysis

Projects in the architectural, engineering, and construction (AEC) industry often experience cost overruns and are not nished according to schedule [41]. The greatest potential for overcoming these challenges lies in the industry's digital transformation, spearheaded by the growing adoption of BIM-based methods and technologies [42, 43] [3]. Building Information Modeling (BIM) establishes a joint digital knowledge base from which all AEC stakeholders can preserve and share all relevant project information during any phase of the construction lifecycle. Therefore, interoperability, data exchange across multiple domains, is an essential feature of the BIM process [44]. In particular, a fully integrated, digitalized design environment involving architects and structural engineers necessitates the ability for data exchange between computer-aided design (CAD) and computer-aided engineering (CAE) software. Using BIM for such engineering analysis purposes has the potential to save time and cost through automation and to achieve higher quality and better performance in buildings [45 48].

However, according to a McGraw Hill industry survey, despite having the highest frequency index, which measures the frequency with which BIM is used for a process, structural analysis had the second-lowest value/di culty ratio among industrial professionals [3]. In other words, there is a high demand for BIM interoperability for structural analysis, but this particular BIM use is currently ine cient for industry practice. Currently, model-based data exchange between BIM-based software in the CAD and CAE domains falls short of full interoperability, resulting in loss of data and/or extensive remodeling e orts [49 51]. Improving BIM interoperability is key to achieving an integrated design-construction environment that enables risk-informed

decision-making for project deviations.

IV.1.2 Open vs Closed BIM Data Exchange

The BIM work ow is particularly advantageous for facilitating data exchange between the architectural (CAD) and structural analysis (CAE) domains [52]. Two categories of BIM-based data exchange are 1) closed BIM and 2) open BIM [53].

Closed BIM describes a work ow in which two distinct software environments are linked via a plug-in designed for that speci c purpose. The closed BIM approach appears to be highly e ective, but the methods used are proprietary and cannot be applied to other software tool combinations. Conversely, open BIM involves the use of a third-party, non-proprietary, and open format for data exchange. Industry Foundation Classes (IFC) is the most used open and non-proprietary format for BIM data exchange [54]. Third-party, non-proprietary data exchange is considered the most promising solution for the digitalization of the AEC industry, for reasons such as:

- O ces often choose a single software tool catering to the speci c needs of their domain [55]; Therefore, it is not feasible to expect the propagation of proprietary plug-ins to cover all possible software tool combinations that may occur in future collaborations on AEC projects.
- No single software package can cover all the domains of an AEC project without the need for data exchange with other software [44]
- Open formats for data exchange allow for long-term preservation and access to data across a project's lifecycle [56].

IV.1.3 Industry Foundations Classes (IFC)

Industry Foundation Classes (IFC) is the standard format for open and non-proprietary BIM model-based data exchange. IFC characterizes objects, their properties, and their

relationships, and over 150 software tools claim to support the IFC schema, either for import and/or export of IFC data models, including leading CAD and CAE software applications. IFC is developed by buildingSMART International (bSI) and is ISO certi ed (ISO 16739-1:2018)[54]. IFC is the foundation of a collaborative BIM lifecycle and aims to guarantee the interoperability of independent BIM software [57].

The IFC schema employs sub-schema implementations, known as Model View De nitions (MVD). An MVD describes and facilitates a particular use or work ow. Di erent MVDs can accommodate varied con gurations and model representations. For example, a beam can be represented by a line segment between two points in the Structural Analysis View (SAV) MVD or a 3D geometric object by way of extruded solids or triangulated surfaces in the Reference View (RV) MVD. IFC MVDs are the basis by which bSI certi es software for IFC compliance. For example, Autodesk Revit is certi ed for IFC4 RV import and export [54].

The two standard versions of IFC used in practice are IFC2x3 and IFC4, each of which has several o cial bSI MVDs associated with their use. IFC2x3 Coordination View (CV) [58], the most widely implemented MVD, is a wide schema developed for design coordination between architectural, structural, and building services (MEP) domains and is currently the only IFC2x3 MVD being regularly maintained by bSI [54]. IFC2x3 Structural Analysis View (SAV) represents information related to structural engineering and analysis, including loads, constraints, boundary conditions, materials, and element connectivity [59]. The most recent version of IFC is IFC4, released in 2013. IFC4 purports to introduce several improvements over previous versions and is recommended by bSI for all current developments [60]. IFC4 introduces two new MVDs: the Reference View (RV) and the Design Transfer View (DTV). The IFC4 RV is designed to operate within the con nes of work ows where models are imported with precise geometry as read-only les for referencing and clash detection. In contrast, the IFC4 DTV is intended for handover

work ows where models are imported with parametric geometry with the intention of further editing. IFC4 DTV can be considered the successor MVD to IFC2x3 CV, but IFC4 DTV is still in draft status, whereas the IFC4 RV is o cially nished and is available for software certi cation [54]. The IFC2x3 SAV is not present as an o cial MVD for IFC4, but the data structures and hierarchies required for Structural Analysis View have carried over into IFC4. Out of all the available common MVDs, CV, RV, DTV, and SAV, only the SAV MVD is the most suitable format for the representation of a structural analysis model, particularly for de ning connectivity between elements [43].

IFC-based BIM data exchange o ers several advantages, including the ability to combine di erent functionalities of software via non-proprietary methods and multi-disciplinary sharing of project materials across a project lifecycle [61]. However, there are also disadvantages to the IFC approach, as highlighted in the critical reviews conducted by Gerbino [51] and Sibenik [50] in the next section.

IV.1.4 State of BIM Interoperability via IFC and Past Research E orts

Gerbino 2021 [51] conducted a literature review and a 3-year comparative study on the current issues users face with CAD-to-CAE interoperability even when using the IFC open le format. Gerbino assessed the software performance of four common CAD and six common CAE software for three levels of interoperability: 1) CAD-to-CAD, 2) CAD-to-CAE, and 3) CAE-to-CAE. Horizontal interoperability involves data exchange across software environments within the same domain, such as CAD-to-CAD and CAE-to-CAE, whereas vertical interoperability involves data exchange across di erent domains, such as CAD-to-CAE and CAE-to-CAD. Gerbino notes that there is a dearth of both research and software implementation for the most recent IFC4 schema, even though it was released as far back as 2013. Horizontal interoperability via IFC across CAD platforms is generally satisfactory, although one must note that the sample model used by Gerbino is limited in the number of structural components tested, as it only contained linear elements such

as beam and columns and no planar elements such as slabs and walls. However, vertical interoperability faces many issues, particularly regarding missing elements and lack of element connectivity. Also, Gerbino notes that CAE-to-CAD interoperability via the IFC4 DTV is not yet e cient. Gerbino concludes that all the aforementioned challenges with IFC data exchange push software developers to rely more on direct exchange solutions in the form of proprietary plug-ins, which aligns with the closed BIM approach as opposed to open BIM [51].

Sibenik 2020 [50] also conducts a literature review and comparative software study to assess the performance of CAD-to-CAE interoperability but focuses on more of the systemic issues a ecting IFC implementation and data exchange within the broader AEC industry. Sibenik's literature review found that the majority of the research e orts of the academic community have focused on improving BIM-based data exchange via the IFC open le format [43, 49, 62 72]. Sibenik notes that the IFC-based data exchange improvement proposals of the academic community have not been widely adopted in practice due to the heterogeneity of the AEC industry, and interoperability continues to progress slowly [48]. Sibenik identi es broader systemic issues facing BIM interoperability via IFC by examining the processes a ecting data exchange practices within a conceptualized two-level ecosystem of the AEC industry [73, 74]. The project level refers to IFC data exchange as perceived by the end-users, such as an architect exporting an IFC2x3 CV from the CAD software Revit and a structural engineer importing that IFC into the CAE software SAP2000. The inter-organization level refers to higher-level processes of AEC stakeholders, namely IFC software certi cation, IFC and rules standardization, and software development. Sibenik's [50] comparative study of CAD-to-CAE interoperability notes that many issues a ect vertical interoperability performance between software, which echoes Gerbino's ndings. However, Sibenik notes that the faults in IFC implementation for software at the project level are downstream of broader issues at the inter-organizational level. Namely, Sibenik points to the lack of

appropriate MVDs and interpretation rules for exchanging model data between CAD and CAE domains as well as the limited e cacy and con dence in the IFC certi cation process, which are systemic issues independent from software development. Sibenik concludes that a top-down approach with respect to IFC data exchange issues within the AEC ecosystem is ultimately necessary to improve interoperability [50].

Figure IV.1 qualitatively summarizes the issues facing BIM CAD-to-CAE interoperability via IFC at the project level within the AEC ecosystem, as de ned by Sibenik 2020 [50]. The qualitative observations within Figure IV.1 are supported by the ndings of the literature reviews and interoperability tests conducted by Sibenik 2020 [50] and Gerbino 2021 [51] as well as the author's own interoperability tests, as shown in Section IV.3. Each arrow represents the e cacy of either an export or import process of model data using IFC. Note that there is no satisfactory process path for vertical interoperability, either for CAD-to-CAE or CAE-to-CAD. Despite the systemic issues facing IFC-based data exchange, Sibenik 2020 notes that the most promising proposals for improving the current state of CAD-to-CAE interoperability are those intended to be software-independent, thereby adhering to Open BIM principles [50]. One such proposal that adheres to open BIM principles via IFC is the interoperability tool developed by Ramaji 2018 [43].

Ramaji 2018 [43] presents a mechanism for enabling CAD-to-CAE interoperability that uses the open BIM approach via IFC for both import and export of model information. Ramaji notes that many past research e orts rely on proprietary le formats for importing or exporting model information. Therefore, Ramaji develops a tool that aims to convert architectural design information of primary building elements, such as beams, columns, slabs, and walls, from IFC2x3 CV to IFC2x3 SAV. Ramaji chooses the SAV MVD as the export format because it is the most appropriate for representing structural model information within the IFC format, particularly for its

ability to de ne element connectivity, unlike other MVDs. The tool uses four primary interpretation mechanisms:

1. Conversion of linear elements (i.e., IfcBeam, IfcColumn, IfcMember) in CV to their equivalent representations in SAV (i.e.IfcStructuralCurveMember)
2. Conversion of planar elements (IfcSlab, IfcWall) in CV to their equivalent representations in SAV (IfcStructuralSurfaceMember)
3. Material property enrichment
4. Element connectivity adjustment

Ramaji's [43] interoperability tool essentially operates as an MVD translator between IFC2x3 CV to IFC2x3 SAV, which, in principle, allows for wider applicability of the IFC2x3 SAV MVD for use in importing architectural designs into structural analysis software. However, the tool is limited to the interpretation of prismatic elements whose 3D representation within IFC is given by simpli ed extruded area solids, as opposed to more complex tessellated objects. Additionally, the validation study of the four interpretation mechanisms is limited to only one structural building model provided by bSI, so the broader applicability to other commercial-based CAE software cannot be evaluated [43].

Figure IV.1: BIM Interoperability Using IFC Following Existing Practice

Color Map for Process Arrows:
Green ! Supported by many or some software, and the supporting software generally perform well
Yellow ! Supported by some software, and the supporting software perform well or with mixed results
Red ! Supported by some or few software, and the supporting software perform with mixed results or inadequately

IV.1.5 Research Objectives of the Current Study

Ramaji 2018's [43] BIM interoperability tool that converts BIM model data from IFC2x3 CV to IFC2x3 SAV shows promise for the potential of IFC-based open BIM solutions to improve the current state of CAD-to-CAE interoperability at the project level until the broader systemic issues a ecting interoperability at the inter-organizational level are addressed in a top-down approach, as described in Sibenik 2020 [50]. Therefore, to further advance open-BIM interoperability solutions at the project level, the objective of the current study is to develop an IFC-based CAD-to-CAE interoperability tool with novel

and robust interoperability mechanisms to address some areas lacking in previous research proposals, as listed below.

- To address the need for more open BIM-focused solutions, i.e. frameworks where IFC is used for both the import and export of model information, the proposed interoperability tool takes in CAD data of primary building objects, i.e. beams, columns, slabs, and walls, as architectural IFC les, namely IFC4 RV or IFC4 DTV, as input and converts it to the IFC SAV format for use in import with CAE software.
- To address the lack of research into data exchange involving the latest version of the IFC schema, the proposed interoperability tool is developed for use with the IFC4 schema.
- To address the lack of IFC data exchange solutions that aren't limited to the extruded area solid representation for building elements, the proposed interoperability tool aims for compatibility with any solid body representation of IFC objects, such as tessellated geometry for beams.
- To address the need to compensate for the lack of element connectivity information in architectural IFC les, the proposed interoperability tool presents two new element connectivity mechanisms, one for automating frame member connectivity and another automating slab-to- oor-beam-system connectivity, that aim to produce a complete connected mesh ready for structural analysis.
- To ensure that the proposed interoperability tool is capable of improving industry practice, the tool is tested and validated using common commercial BIM-based software.

Figure IV.2 shows a qualitative overview of the value added by the proposed interoperability tool to the existing practice of IFC-based BIM model data exchange. Note that the inclusion of the tool allows a satisfactory process path from CAD to CAE domains using IFC. The tool is tested against the starred CAD and CAE software, Revit,

E3D Design, ArchiCAD, SAP2000, RFEM, and ANSYS, which are listed in Table IV.1. ANSYS is not an IFC-based software, but the CAE software is included to showcase how the open-BIM framework of the tool can be expanded to include proprietary data formats that store structural analysis information in a manner similar to IFC SAV.

IV.1.6 Chapter Organization

This chapter is organized as follows:

- Section IV.2 lists the BIM-based CAD and CAE software and the accompanying architectural building models that are under study.
- To assess the current state of interoperability, Section IV.3 presents an interoperability assessment of one-way IFC-based building BIM model data exchange between the selected CAD and CAE software using existing practice.
- Section IV.4, Section IV.5, and Section IV.6 discuss the development and practical application of the author's BIM interoperability tool.

  Section IV.4 discusses the methodology and development of the interoperability tool.

  Section IV.5 showcases the tool's application and summarizes the building models' conversion from the architectural domain to the structural domain.

  In contrast to the previous interoperability assessment that uses only existing practice, Section IV.6 presents an interoperability assessment of one-way IFC-based building BIM model data exchange between the selected CAD and CAE software using the author's interoperability tool.
- Section IV.7 discusses the improvements in BIM interoperability by comparing the results from the interoperability assessments of Section IV.3 and Section IV.6.
- Section IV.8 provides a summary and conclusion of this research.

Figure IV.2: BIM Interoperability Using IFC With Author's Interoperability Tool

Color Map for Process Arrows:
Green ! Supported by many or some software, and the supporting software generally perform well
Yellow ! Supported by some software, and the supporting software perform well or with mixed results
Red ! Supported by some or few software, and the supporting software perform with mixed results or inadequately

IV.2 BIM-based Software and IFC Files of Building Models Used in this Study

This section lists and describes the BIM-based computer-aided design (CAD) and computer-aided engineering (CAE) software and the accompanying IFC les of various architectural building designs used for the vertical (CAD-to-CAE) BIM interoperability assessments in Section IV.3 and Section IV.6 of this chapter.

IV.2.1 BIM-based Software Used in this Study

This study assesses the one-way interoperability from three BIM-based CAD to three CAE software. Table IV.1 details these commonly used BIM-based software, their parent companies, their versions, and a link to the respective companies' websites. To assess the current IFC capabilities of the software under consideration, the author employs the most recent versions readily available at the time of writing in August 2023.

Table IV.2 and Table IV.3 list the IFC import and export capabilities of each CAD and CAE application on a binary basis. In other words, Table IV.2 and Table IV.3 do not evaluate the relative performance or quality of IFC capabilities, but simply report whether a given software provides some level of support for a given IFC functionality. Therefore, each software's IFC import and export capabilities are determined by satisfying one or more of the following three criteria:

1. O cial software documentation details IFC import and/or export functionality
2. buildingSMART International (bSI) certi es or is in the process of certifying the software for IFC export and/or import functionality
3. Author conducts rsthand testing of IFC import and/or export functionality

IFC capabilities di er by software, IFC schema, and IFC MVD. The variance in IFC support across software limits which IFC le types may be considered for the upcoming

CAD-to-CAE interoperability tests in Section IV.3 and Section IV.6. For example, the CAD software Revit and ArchiCAD support IFC4 DTV export, while E3D Design does not. Additionally, ArchiCAD supports IFC2x3 SAV export, while the other two CAD software do not o er any support for IFC SAV. All three CAD software, Revit, ArchiCAD, and E3D Design, support IFC4 RV export.

Table IV.1: List of BIM-based Software Adopted for Building Interoperability Tests

Platform	Company	Software	Version	Website
CAD	Autodesk	Revit [75]	2024	www.autodesk.com
	AVEVA	E3D Design [76]	3.1.3.0	www.aveva.com
	Graphisoft	ArchiCAD [77]	26.0.0	www.graphisoft.com
CAE	CSI	SAP2000 [78]	23.0.0	www.csiamerica.com
	Dlubal	RFEM [79]	6.02	www.dlubal.com
	ANSYS	Mechanical APDL [80]	2022 R2	www.ansys.com

CAD ! Computer Aided Design
CAE ! Computer Aided Engineering

IV.2.2 IFC Files of Building Models Used in this Study

Three custom-built and three commercial models of architectural building designs are considered for the CAD-to-CAE interoperability tests in Section IV.3 and Section IV.6. Table IV.4 lists the six models, their authoring software, and their accompanying IFC les.

Three custom-built models manually created by the author as native IFC4 RV les using IfcOpenShell are shown in Figure IV.3, Figure IV.4, and Figure IV.5. IfcOpenShell is an open-source IFC toolkit and geometry engine that provides an API for reading, writing, and modifying BIM models using IFC [81]. These custom-built models are intended to assist in the development of the author's BIM Interoperability Tool and serve as a benchmark for evaluating the performance of IFC model data exchange with BIM-based software. These models contain the most common IFC building elements, such as

Table IV.2: Support for IFC Import in Computer Aided Design (CAD) and Computer Aided Engineering (CAE) Software

Platform	Software	IFC2x3 MVD		IFC4 MVD		
		CV	SAV	RV	DTV [a]	SAV[b]
CAD	Revit	✓[c]	X	✓[c]	✓	X
	E3D Design	✓[d]	X	✓	✓	X
	ArchiCAD	✓[c]	✓	✓[c]	✓	✓
CAE	SAP2000	✓	✓	✓	✓	✓
	RFEM	✓[c]	✓	✓	✓	✓
	Mechanical APDL	X	X	X	X	X

[a]IFC4 DTV is a formal buildingSMART International (bSI) MVD in draft status
[b]IFC2x3 SAV is a formal bSI MVD, but IFC4 SAV is not
[c]bSI certi ed
[d]bSI certi cation in progress

Table IV.3: Support for IFC Export in Computer Aided Design (CAD) and Computer Aided Engineering (CAE) Software

Platform	Software	IFC2x3 MVD		IFC4 MVD		
		CV	SAV	RV	DTV [a]	SAV[b]
CAD	Revit	✓[c]	X	✓[c]	✓	X
	E3D Design	✓[c]	X	✓	X	X
	ArchiCAD	✓[c]	✓	✓[c]	✓	X
CAE	SAP2000	✓	✓	✓	X	✓
	RFEM	X	X	✓	X	✓
	Mechanical APDL	X	X	X	X	X

[a]IFC4 DTV is a formal buildingSMART International (bSI) MVD in draft status
[b]IFC2x3 SAV is a formal bSI MVD, but IFC4 SAV is not
[c]bSI certi ed

IfcBeam, IfcColumn, and IfcSlab, and the IFC representation type for all these elements is SweptSolid, which is a simple and e cient parametric representation of a wide variety of complex shapes, such as I-beam sections and convex slabs.

The rst custom-built model is the AuthorSimpleStructure created in IfcOpenShell. Figure IV.3 depicts an IFC viewer representation of the IFC4 RV le, while Table IV.5

depicts the IFC4 RV building elements included in the model. This small model enables a rapid evaluation of the e cacy of IFC model data exchange for a simple design with few elements. There are three essential IFC building components present: IfcBeam, IfcColumn, and IfcSlab. The various section types and materials of the beams and columns facilitate a comparative evaluation of the IfcBeam and IfcColumn model data exchange. The small, convex shape of the slab facilitates the evaluation of model data exchange for the most elementary IfcSlab designs.

The second custom-built model is the AuthorEuroBeams created in IfcOpenShell. Figure IV.4 depicts an IFC viewer representation of the IFC4 RV le, while Table IV.6 depicts the IFC4 RV building elements included in the model. This custom-built model is not an actual building structure, but it does include the most common beam section types, such as I-beams, C-beams, T-beams, L-beams, solid and hollow rectangular beams, and solid and hollow circular beams, as well as di erent orientations of these shapes. This model facilitates the evaluation of IFC model data exchange for di erent beam shapes and orientations.

The third custom-built model is the AuthorLargeStructure created in IfcOpenShell. Figure IV.5 depicts an IFC viewer representation of the IFC4 RV le, while Table IV.7 depicts the IFC4 RV building elements included in the model. This custom-built model contains multiple levels, a oor beam system with girders and joists, and a slab with a concave shape. This model facilitates the evaluation of IFC model data exchange for a larger, more complex building design than the AuthorSimpleStructure model.

The three commercial models depicted in Figure IV.6, Figure IV.7, and Figure IV.8 are architectural building designs created in their respective CAD software or extracted from sample projects provided by the developer. These commercial models are used to demonstrate interoperability performance for practical applications. The building models are exported to IFC les using the IFC export functionality of the CAD software.

The author created the Revit SteelConstruction model by following an online tutorial shown on the Balkan Architect YouTube channel [82]. Figure IV.6 shows the original model along with the exported IFC le representations while Table IV.8 depicts the IFC4 RV building elements included in the model. The SteelConstruction model is a three-story steel-framed structure with concrete oor slabs and an interior concrete core. The model is exported to both IFC4 RV and IFC4 DTV.

AVEVA provides an E3D Design sample project containing the BuildingB02 model. Figure IV.7 shows the original model along with the exported IFC le representations while Table IV.9 depicts the IFC4 RV building elements included in the model. The BuildingB02 model is a three-story steel-framed structure whose concrete oor slabs have large perforations. The model is exported to IFC4 RV.

Graphisoft provides an ArchiCAD sample project containing the SO ce model. Figure IV.8 shows the original model along with the exported IFC le representations while Table IV.10 depicts the IFC4 RV building elements included in the model. The SO ce model is a four-story steel-framed structure with concrete oor slabs and an interior concrete core. The model is exported to IFC2x3 SAV, IFC4 RV, and IFC4 DTV.

Table IV.4: IFC Files Used in Building Study - Exported by BIM-based CAD Software

Software	Model Creator	Model Name	Exported IFC File(s)	IFC MVD	Description
IfcOpenShell	Thesis Author	AuthorSimpleStructure	AuthorSimpleStructure_RV.ifc	IFC4 RV [a]	Author-created simple structure
IfcOpenShell	Thesis Author	AuthorEuroBeams	AuthorEuroBeams_RV.ifc	IFC4 RV [a]	Author-created assembly of beams
IfcOpenShell	Thesis Author	AuthorLargeStructure	AuthorLargeStructure_RV.ifc	IFC4 RV [a]	Author-created large structure
Revit	Balkan Architect (YT Channel) [82]	SteelConstruction	SteelConstruction_RV.ifc SteelConstruction_DTV.ifc	IFC4 RV IFC4 DTV	From online Revit tutorial on steel construction
E3D Design	AVEVA	BuildingB02	BuildingB02_RV.ifc	IFC4 RV	From AVEVA ProjAPS sample model
ArchiCAD	Graphisoft SE	SO ce	SO ce_RV.ifc SO ce_DTV.ifc SO ce_SAV.ifc	IFC4 RV IFC4 DTV IFC2x3 SAV	From ArchiCAD S-O ce sample model

[a] Author's custom IFC4 format created using IfcOpenShell and based on the IFC4 RV MVD

Figure IV.3: IfcOpenShell AuthorSimpleStructure Model (IFC4 RV)

Table IV.5: IFC4 RV Elements of IfcOpenShell AuthorSimpleStructure Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S355 Steel	HE240B	-	4
IfcColumn	C30/37 Concrete	Rect. 450x300	-	4
IfcSlab	C30/37 Concrete	-	200	1

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

Figure IV.4: IfcOpenShell AuthorEuroBeams Model (IFC4 RV)

Table IV.6: IFC4 RV Elements of IfcOpenShell AuthorEuroBeams Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S355 Steel	HE400A	-	2
IfcBeam	S355 Steel	UPN400	-	4
IfcBeam	S355 Steel	T-HE200A/.65/	-	4
IfcBeam	S355 Steel	L150X100X14	-	4
IfcBeam	C30/37 Concrete	Rect. 457x254	-	2
IfcBeam	S275 Steel	TUBO400X280X30	-	2
IfcBeam	C25/30 Concrete	Circle 305	-	1
IfcBeam	S275 Steel	TUBO-D298.5X5.9	-	1

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

Figure IV.5: IfcOpenShell AuthorLargeStructure Model (IFC4 RV)

Table IV.7: IFC4 RV Elements of IfcOpenShell AuthorLargeStructure Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S355 Steel	HLS160	-	5
IfcBeam	S355 Steel	HE200B	-	4
IfcBeam	S355 Steel	HE260A	-	8
IfcColumn	S355 Steel	HE300B	-	8
IfcSlab	C30/37 Concrete	-	200	2

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

(a) Original Model

(b) IFC4 RV

(c) IFC4 DTV

Figure IV.6: Revit SteelConstruction Model and Exported IFC Files

Table IV.8: IFC4 RV Elements of Revit SteelConstruction Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S275 Steel	UB254x102x28	-	27
IfcBeam	S275 Steel	UB406x178x60	-	12
IfcColumn	S275 Steel	UC305x305x97	-	8
IfcSlab	C35/45 Concrete	-	210	3
IfcWall	Generic Concrete	-	300	4

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

(a) Original Model

(b) IFC4 RV

Figure IV.7: E3D Design BuildingB02 Model and Exported IFC File

Table IV.9: IFC4 RV Elements of E3D Design BuildingB02 Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S355 Steel	UB356X127X33	-	16
IfcBeam	S355 Steel	UB203X133X25	-	48
IfcBeam	S355 Steel	UB305X127X42	-	33
IfcColumn	S355 Steel	UC305X305X137	-	15
IfcSlab	C25/30 Concrete	-	200	4

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

(a) Original Model

(b) IFC4 RV

(c) IFC4 DTV

(d) IFC2x3 SAV

Figure IV.8: ArchiCAD SO ce Model and Exported IFC Files

Table IV.10: IFC4 RV Elements of ArchiCAD SO ce Model

IFC Class	Material	Designation[a]	Thickness (mm)	No.
IfcBeam	S275 Steel	Rect. 240x240	-	28
IfcBeam	S275 Steel	HE240B	-	176
IfcColumn	S275 Steel	Rect. 240x240	-	14
IfcColumn	S275 Steel	HE240B	-	88
IfcWall	C30/37 Concrete	-	250	32
IfcSlab	C30/37 Concrete	-	150/305[b]	4

[a]Rectangle (height x base) and Circle (diameter) section dimensions in millimeters

[b]Roof is 150mm steel deck with concrete plus 155mm insulation on top

IV.3 Interoperability Assessment #1: Building Model Data Exchange Using IFC and Existing Practice

This section presents an assessment of one-way IFC-based BIM interoperability between CAD and CAE software using existing practice, as depicted in Figure IV.1. The purpose of this assessment is to emphasize the de ciencies in IFC-based interoperability between the speci c CAD and CAE software listed in Table IV.1. This assessment is not meant to be a comprehensive comparative study for generalizing IFC-based interoperability performance of CAD and CAE software. As depicted in Table IV.4, six models of architectural building structures, three custom-built utilizing IfcOpenShell, and three produced utilizing the three commercial CAD software, Revit, E3D Design, and ArchiCAD, generate a total of nine IFC les used in this study. ANSYS Mechanical APDL is not considered for this evaluation because it lacks IFC support.

The assessment is performed by importing IFC les of architectural building designs from three CAD software into two CAE software, SAP2000 and RFEM. The interoperability assessment results for SAP2000 and RFEM are displayed in Table IV.11 and Table IV.12, respectively. The performance of CAD-to-CAE interoperability is evaluated based on the perceived amount of rework required by a hypothetical structural engineer to rectify the de ciencies in imported building models to prepare them for structural analysis. The essential model data exchange components outlined below are graded using a qualitative scale:

- Geometry, materials, and section data for structural frame members
- Geometry, materials, and thickness for structural slabs and walls
- Connectivity between linear elements of the analytical model, i.e., element connectivity between structural frame members
- Connectivity between linear elements and horizontal planar elements of the

analytical model, i.e., element connectivity between oor beams and slabs

- ˆ Connectivity between horizontal planar elements and vertical planar elements of the analytical model, i.e., element connectivity between structural slabs and core wall structures
- ˆ General model readiness for structural analysis and use as a reference for the original design

The qualitative grading scale for interoperability performance is de ned as follows:

- ˆ 0 Completely missing information and/or substantial rework required
- ˆ 1 Some information missing and/or moderate rework required
- ˆ 2 Nearly all or all information present and/or minimal to no rework required

IV.3.1 Interoperability Assessment: Building Model Data Exchange from CAD Software to SAP2000 Using IFC and Existing Practice

This subsection presents an assessment of one-way IFC-based building BIM interoperability between the CAD software Revit, E3D Design, and ArchiCAD, and the CAE software, SAP2000, using existing practice.

IfcOpenShell IFC Imported to SAP2000

The rst part of the interoperability assessment in this subsection evaluates the performance of importing three custom-built models, which are in the form of IFC4 RV les created using IfcOpenShell, into the CAE software SAP2000. This assessment establishes a baseline for evaluating IFC-based model data exchange using les not generated by commercial software. Section IV.2 describes the three custom-made models, named AuthorSimpleStructure, AuthorEuroBeams, and AuthorLargeStructure. The interoperability performances of the three IFC les of the custom-built IfcOpenShell models are summarized in the row labeled IfcOpenShell in Table IV.11 and are

graphically represented in Figure IV.9, Figure IV.10, and Figure IV.11. The following are general observations regarding the import of IFC4 RV les into SAP2000 for the three custom-built models:

- SAP2000 recognizes all structural information except there is improper placement of the IfcSlab, and there is no element connectivity.
- The imported models require minimal rework before being used as a design reference.
- Due to the lack of connectivity, the imported models require substantial rework before being used for structural analysis.

Revit IFC Imported to SAP2000

The second part of the interoperability assessment in this subsection evaluates the performance of importing one Revit model of a multi-story steel framed structure, which is exported in the form of one IFC4 RV le and one IFC4 DTV le, into the CAE software SAP2000. Section IV.2 describes the Revit model, named SteelConstruction. The interoperability performances of the two IFC les of the Revit model are summarized in the rows labeled Revit in Table IV.11 and are graphically represented in Figure IV.12. The following are general observations regarding the import of the IFC4 RV le into SAP2000 for the Revit SteelConstruction Model:

- SAP2000 recognizes IfcBeam geometry but not section data, no IfcSlab or IfcWall elements are imported, material information is missing, and there is no connectivity.
- Due to the missing beam section data and slab and wall elements, the imported models require substantial rework before being used as a design reference.
- Due to the issues listed above as well as the lack of connectivity, the imported model requires substantial rework before being used for structural analysis.

The following are general observations regarding the import of the IFC4 DTV le into SAP2000 for the Revit SteelConstruction Model:

- SAP2000 recognizes IfcBeam geometry and section data but some beam orientations are incorrect, IfcSlab geometry and thickness are correct, IfcWall elements are missing, material information is missing, and there is no connectivity.
- Due to the missing wall elements, the imported models require substantial rework before being used as a design reference.
- Due to the issues listed above as well as the lack of connectivity, the imported model requires substantial rework before being used for structural analysis.

E3D Design IFC Imported to SAP2000

The third part of the interoperability assessment in this subsection evaluates the performance of importing one E3D Design model of a multi-story steel framed structure, which is exported in the form of one IFC4 RV le, into the CAE software SAP2000. Section IV.2 describes the E3D Design model, named BuildingB02. The interoperability performance of the IFC RV le of the E3D Design model is summarized in the row labeled E3D in Table IV.11 and is graphically represented in Figure IV.13. The following are general observations regarding the import of the IFC4 RV le into SAP2000 for the E3D Design BuildingB02 Model:

- SAP2000 fails to recognize the tessellated geometry of any of the IFC elements, and material information is missing.
- Due to the complete failure to import the model, there can be no use for either design reference or structural analysis.

ArchiCAD IFC Imported to SAP2000

The fourth part of the interoperability assessment in this subsection evaluates the performance of importing one ArchiCAD model of a multi-story steel framed structure, which is exported in the form of three IFC les, IFC4 RV, IFC4 DTV, and IFC2x3 SAV, into the CAE software SAP2000. Section IV.2 describes the ArchiCAD model, named

SO ce. The interoperability performances of the three IFC les of the ArchiCAD model are summarized in the rows labeled ArchiCAD in Table IV.11 and are graphically represented in Figure IV.14. The following are general observations regarding the import of the IFC4 RV le into SAP2000 for the ArchiCAD SO ce Model:

- SAP2000 fails to recognize the tessellated geometry of any of the IFC elements, and material information is missing.
- Due to the complete failure to import the model, there can be no use for either design reference or structural analysis.

The following are general observations regarding the import of the IFC4 DTV le into SAP2000 for the ArchiCAD SO ce Model:

- SAP2000 recognizes all IfcBeam and IfcColumn geometry but no section data and some frame members are already missing from the initial IFC4 DTV export from ArchICAD. IfcSlab and IfcWall elements are missing. Lastly, there is no element connectivity.
- Due to the missing IfcSlab and IfcWall elements, the imported model requires substantial rework before being used as a design reference.
- Due to the issues listed above as well as the lack of connectivity, the imported model requires substantial rework before being used for structural analysis.

The following are general observations regarding the import of the IFC2x3 SAV le into SAP2000 for the ArchiCAD SO ce Model:

- SAP2000 recognizes the geometry for frame members and IfcWalls, IfcSlab elements are missingm beam section data is not recognized, and material information is missing. Element connectivity is satis ed for structural framing, but due to the missing slabs, the core structure does not connect to the building.
- Due to the missing slabs and beam section data, the imported model requires

substantial rework before being used as a design reference.

- Due to the issues listed above as well as the lack of connectivity for the core structure to the building, the imported model requires substantial rework before being used for structural analysis.

Table IV.11: Summary for Assessment of IFC-based BIM Interoperability from CAD to SAP2000 Following Existing Practice

CAD Software	IFC MVD	Beams and Columns			Slabs and Walls			Element Connectivity			Model Readiness	
		Geometry	Materials	Section Data	Geometry	Materials	Thickness	Structural Framing	Slabs to Floor Beams	Core Structure	For Structural Analysis	For Design Reference
IfcOpenShell	IFC4 RV [a]	2	2	2	1	2	2	0	0	N/A	0	2
Revit	IFC4 RV [b]	1	0	0	0	0	0	0	0	0	0	0
	IFC4 DTV [b]	1	0	2	0	0	1	0	0	0	0	0
E3D	IFC4 RV [b]	0	0	0	0	0	0	0	0	N/A	0	0
ArchiCAD	IFC4 RV [b]	0	0	0	0	0	0	0	0	0	0	0
	IFC4 DTV [b]	1	0	0	0	0	0	0	0	0	0	0
	IFC2x3 SAV [b]	1	0	0	0	0	1	2	0	0	0	0

0 ! Completely missing / substantial rework required
1 ! Some information missing / moderate rework required
2 ! Nearly all or all information present / minimal to no rework required
[a]IFC le created directly by Author in IfcOpenShell
[b]IFC le exported from commercial CAD software

(a) IFC4 RV (b) IFC4 RV to SAP2000

Figure IV.9: Importing IFC File of IfcOpenShell AuthorSimpleStructure Model into SAP2000

(a) IFC4 RV (b) IFC4 RV to SAP2000

Figure IV.10: Importing IFC File of IfcOpenShell AuthorEuroBeams Model into SAP2000

(a) IFC4 RV (b) IFC4 RV to SAP2000

Figure IV.11: Importing IFC File of IfcOpenShell AuthorLargeStructure Model into SAP2000

(a) IFC4 RV

(b) IFC4 RV to SAP2000

(c) IFC4 DTV

(d) IFC4 DTV to SAP2000

Figure IV.12: Importing IFC Files of Revit SteelConstruction Model into SAP2000

(a) IFC4 RV

(b) IFC4 RV to SAP2000

Figure IV.13: Importing IFC Files of E3D Design BuildingB02 Model into SAP2000

(a) IFC4 RV

(b) IFC4 RV to SAP2000

(c) IFC4 DTV

(d) IFC4 DTV to SAP2000

(e) IFC2x3 SAV

(f) IFC2x3 SAV to SAP2000

Figure IV.14: Importing IFC Files of ArchiCAD SO ce Model into SAP2000

IV.3.2 Interoperability Assessment: Building Model Data Exchange from CAD Software to RFEM Using IFC and Existing Practice

This subsection presents an assessment of one-way IFC-based building BIM interoperability between the CAD software Revit, E3D Design, and ArchiCAD, and the CAE software, RFEM, using existing practice.

IfcOpenShell IFC Imported into RFEM

The rst part of the interoperability assessment in this subsection evaluates the performance of importing three custom-built models, which are in the form of IFC4 RV les created using IfcOpenShell, into the CAE software RFEM. This assessment establishes a baseline for evaluating IFC-based model data exchange using les not generated by commercial software. Section IV.2 describes the three custom-made models, named AuthorSimpleStructure, AuthorEuroBeams, and AuthorLargeStructure. The interoperability performances of the three IFC les of the custom-built IfcOpenShell models are summarized in the row labeled IfcOpenShell in Table IV.12 and are graphically represented in Figure IV.15, Figure IV.16, and Figure IV.17. The following are general observations regarding the import of IFC4 RV les into RFEM for the three custom-built models:

- RFEM recognizes the IfcBeam and IfcSlab geometry, but does not recognize the I-beam section data, and there is no element connectivity.
- Due to missing beam section data, the imported models require moderate rework before being used as a design reference.
- Due to missing beam section data and lack of connectivity, the imported models require substantial rework before being used for structural analysis.

Revit IFC Imported into RFEM

The second part of the interoperability assessment in this subsection evaluates the performance of importing one Revit model of a multi-story steel framed structure, which is exported in the form of one IFC4 RV le and one IFC4 DTV le, into the CAE software RFEM. Section IV.2 describes the Revit model, named SteelConstruction. The interoperability performances of the two IFC les of the Revit model are summarized in the rows labeled Revit in Table IV.12 and are graphically represented in Figure IV.18. The following are general observations regarding the import of the IFC4 RV and IFC4 DTV les into RFEM for the Revit SteelConstruction Model:

- RFEM recognizes IfcBeam geometry but not the section data, RFEM recognizes IfcSlab and IfcWall geometry and thickness, material information is missing, and there is no element connectivity.
- Due to missing beam section data and material information, the imported models require moderate rework before being used as a design reference.
- Due to missing beam section data, material information, and the lack of connectivity, the imported models require substantial rework before being used for structural analysis.

E3D Design IFC Imported into RFEM

The third part of the interoperability assessment in this subsection evaluates the performance of importing one E3D Design model of a multi-story steel framed structure, which is exported in the form of one IFC4 RV le, into the CAE software RFEM. Section IV.2 describes the E3D Design model, named BuildingB02. The interoperability performance of the IFC RV le of the E3D Design model is summarized in the row labeled E3D in Table IV.12 and is graphically represented in Figure IV.19. The following are general observations regarding the import of the IFC4 RV le into RFEM for the

E3D Design BuildingB02 Model:

- RFEM fails to recognize the tessellated geometry of any of the IFC elements, and material information is missing.
- Due to the complete failure to import the model, there can be no use for either design reference or structural analysis.

ArchiCAD IFC Imported into RFEM

The fourth part of the interoperability assessment in this subsection evaluates the performance of importing one ArchiCAD model of a multi-story steel framed structure, which is exported in the form of three IFC les, IFC4 RV, IFC4 DTV, and IFC2x3 SAV, into the CAE software RFEM. Section IV.2 describes the ArchiCAD model, named SO ce. The interoperability performances of the three IFC les of the ArchiCAD model are summarized in the rows labeled ArchiCAD in Table IV.12 and are graphically represented in Figure IV.20. The following are general observations regarding the import of the IFC4 RV le into RFEM for the ArchiCAD SO ce Model:

- RFEM fails to recognize the tessellated geometry of any of the IFC elements, and material information is missing.
- Due to the complete failure to import the model, there can be no use for either design reference or structural analysis.

The following are general observations regarding the import of the IFC4 DTV le into RFEM for the ArchiCAD SO ce Model:

- RFEM recognizes all IfcBeam and IfcColumn geometry and section data, although some frame members are already missing from the initial IFC4 DTV export from ArchICAD and some orientations are incorrect. The beam section data is recognized only because the HEB240 designation name is stored within RFEM's

section database. RFEM recognizes IfcSlab and IfcWall geometry, but the thicknesses are incorrect. Lastly, there is no element connectivity.

- Due to some missing frame members, improper orientations, and incorrect slab and wall thickness, the imported model requires moderate rework before being used as a design reference.
- Due to the issues listed above as well as the lack of connectivity, the imported model requires substantial rework before being used for structural analysis.

The following are general observations regarding the import of the IFC2x3 SAV le into RFEM for the ArchiCAD SO ce Model:

- RFEM recognizes the geometry for all structural elements, beam section data is not recognized, thicknesses are correct, and material information is missing. Element connectivity is satis ed for structural framing and the core structure, but the connectivity between the structural slabs and oor beams is only satis ed at beam-column joints.
- Due to the missing beam section data and material information, the imported model requires moderate rework before being used as a design reference.
- Due to the issues listed above as well as the lack of complete connectivity between the slabs and oor beams, the imported model requires moderate rework before being used for structural analysis.

Table IV.12: Summary for Assessment of IFC-based BIM Interoperability from CAD to RFEM Following Existing Practice

CAD Software	IFC MVD	Beams and Columns			Slabs and Walls			Element Connectivity			Model Readiness	
		Geometry	Materials	Section Data	Geometry	Materials	Thickness	Structural Framing	Slabs to Floor Beams	Core Structure	For Structural Analysis	For Design Reference
IfcOpenShell	IFC4 RV [a]	1	2[c]	0	2	2[c]	2	0	0	N/A	0	1
Revit	IFC4 RV [b]	1	0	0	2	0	2	0	0	0	0	1
	IFC4 DTV [b]	1	0	0	2	0	2	0	0	0	0	1
E3D	IFC4 RV [b]	0	0	0	0	0	0	0	0	N/A	0	0
ArchiCAD	IFC4 RV [b]	0	0	0	0	0	0	0	0	0	0	0
	IFC4 DTV [b]	1	0	2[d]	2	0	0	0	0	0	0	1
	IFC2x3 SAV [b]	1	0	0	2	0	2	2	1	2	1	1

0 ! Completely missing / substantial rework required
1 ! Some information missing / moderate rework required
2 ! Nearly all or all information present / minimal to no rework required
[a]IFC le created directly by Author in IfcOpenShell
[b]IFC le exported from commercial CAD software
[c] IFC les that contain standard material names will be recognized by RFEM, but the custom material properties in the IFC will be ignored.
[d] IFC les that contain standard beam section names will be recognized by RFEM, and the section geometry will be represented. Otherwise, custom section properties can be recognized. Beam sections can also be recognized by a speci c naming convention system used by RFEM

(a) IFC4 RV (b) IFC4 RV to RFEM

Figure IV.15: Importing IFC File of IfcOpenShell AuthorSimpleStructure Model into RFEM

(a) IFC4 RV (b) IFC4 RV to RFEM

Figure IV.16: Importing IFC File of IfcOpenShell AuthorEuroBeams Model into RFEM

(a) IFC4 RV (b) IFC4 RV to RFEM

Figure IV.17: Importing IFC File of IfcOpenShell AuthorLargeStructure Model into RFEM

(a) IFC4 RV

(b) IFC4 RV to RFEM

(c) IFC4 DTV

(d) IFC4 DTV to RFEM

Figure IV.18: Importing IFC Files of Revit SteelConstruction Model into RFEM

(a) IFC4 RV

(b) IFC4 RV to RFEM

Figure IV.19: Importing IFC File of E3D Design BuildingB02 Model into RFEM

(a) IFC4 RV

(b) IFC4 RV to RFEM

(c) IFC4 DTV

(d) IFC4 DTV to RFEM

(e) IFC2x3 SAV

(f) IFC2x3 SAV to RFEM

Figure IV.20: Importing IFC Files of ArchiCAD SO ce Model into RFEM

IV.4 Methodology for Building Model Object Conversion Functions of the Author's Tool

This section describes the methodology for the building model object conversion functions of the author's IFC-based BIM CAD-to-CAE interoperability tool. Figure IV.21 shows a high-level overview of the work ow of the tool, whereby the input is an architectural building design in the form of an IFC4 RV or IFC4 DTV le, and the output is a structural analysis model in the form of an IFC4 SAV le. The tool also outputs an equivalent architectural representation of the IFC4 SAV le in the form of a new IFC4 RV le, but the IFC4 RV le is used for visual reference only. Only the IFC4 SAV le is intended for use with import into CAE software. The tool also has an auxiliary function for converting the IFC4 SAV le into a proprietary le format that is readable by the CAE software ANSYS, but this functionality is not described in the text, as the primary role of the tool is to output IFC model information.

The core functionalities of the interoperability tool are four interpretation mechanisms, listed below:

1. Conversion of Frame Members to Structural Elements (Section IV.4.1)
2. Conversion of Slabs and Walls to Structural Elements (Section IV.4.2)
3. Element Connectivity Adjustment of Frame Members (Section IV.4.3)
4. Element Connectivity Adjustment of Slabs and Floor Beam Systems (Section IV.4.4)

Figure IV.21: BIM Interoperability Tool Work ow AuthorLargeStructure IFC4 RV to IFC4 SAV Case Study

[a] Architectural representation of the IFC4 SAV output, used for visual reference only. Only the IFC4 SAV le is used for vertical interoperability.

Table IV.13: IFC4 Entity De nitions for Building Objects

Model Domain	IFC Class	Entity De nition [83]
Architectural Design	IfcBeam	A horizontal structural member that is capable of withstanding load primarily by resisting bending.
	IfcColumn	A vertical structural member that transmits, through compression, the weight of the structure above to other structural elements below.
	IfcMember	A structural member designed to carry loads between or beyond points of support. The orientation of the member (being horizontal, vertical or sloped) is not relevant to its de nition (in contrary to IfcBeam and IfcColumn).
	IfcSlab	A component of the construction that normally encloses a space vertically. The slab may provide the lower support (oor) or upper construction (roof slab) in any space in a building.
	IfcWall	A vertical construction that bounds or subdivides spaces. Wall are usually vertical, or nearly vertical, planar elements, often designed to bear structural loads.
Structural Analysis	IfcStructuralCurveMember	Instances that describe edge members, i.e. structural analysis idealizations of beams, columns, rods etc.. Curve members may be straight or curved.
	IfcStructuralSurfaceMember	Instances that describe face members, that is, structural analysis idealizations of slabs, walls, and shells. Surface members may be planar or curved.

IV.4.1 Conversion of Frame Members to Structural Elements

This subsection describes the interpretation mechanism used to convert the IFC architectural model representation of frame members (i.e., IfcBeam, IfcColumn, and IfcMember) to their equivalent IFC structural model representation (i.e., IfcStructuralCurveMember). Refer to Table IV.13 for de nitions of these IFC entities. Figure IV.22 shows an example of the conversion of an IfcBeam with SweptSolid representation within an IFC4 RV le to an IfcStructuralCurveMember with Edge representation within a new IFC4 SAV le. The IfcBeam originates from the AuthorLargeStructure IFC4 RV model described in Section IV.2. Table IV.14 summarizes the input and output of the conversion process.

(a) Original IfcBeam from IFC4 RV (b) Converted IfcStructuralCurveMember[a] for IFC4 SAV

Figure IV.22: Frame Member Conversion IfcBeam to IfcStructuralCurveMember for AuthorLargeStructure

[a] IfcEdge representation of the IfcStructuralCurveMember shown in red. Outline of original IfcBeam SweptSolid also shown for visual reference.

Table IV.14: Frame Member Conversion IfcBeam to IfcStructuralCurveMember

Property	Original IFC4 RV Representation	Converted IFC4 SAV Representation
IFC Class	IfcBeam	IfcStructuralCurveMember
RepresentationType	SweptSolid	Edge
Designation	HE260A	HE260A
Material	S355 Steel	S355 Steel
No. of Elements	1	1

The following numbered list summarizes the steps of the frame member conversion process. Figure IV.23 graphically represents several of the steps by using an IfcBeam from

the AuthorLargeStructure model as an example.

1. Geometry Processing

   Processing the IFC geometry of any given frame member object, IfcBeam, IfcColumn, or IfcMember, into a tessellation of surface polygons is a prerequisite for the inference of necessary structural model information, such as spatial locations (step 3), beam shape classi cation (step 5), and section properties (steps 6 and 7). IfcOpenShell-Python [81] is used to process the IFC geometry of the original frame member, shown in Figure IV.22a, which outputs a list of vertices, edges, and faces that are nally arranged into a tessellation of three-sided polygons, shown in Figure IV.23a. This group of triangles represents the tessellation of the original surface of the frame member object and is assigned the variable designation S_1.

2. Inferring the Neutral Axis Direction

   The direction of the neutral axis is necessary for identifying the polygons that constitute the end surfaces, S_3 and S_4, of S_1. The direction of the neutral axis of the frame member is assumed to be parallel with the longest edge line of the longest co-planar polygon subgroup in the polygon group S_1. A co-planar polygon subgroup can be thought of as a continuous at surface of the frame member object. Figure IV.23b shows the identi cation of the bottom ange surface as the longest surface of the example beam, highlighted in yellow. This polygon subgroup is assigned the variable designation S_2. Figure IV.23c marks the longest edge line, designated L_1, of the longest surface of the example beam as a thick black line.

3. Identifying Opposite End Surfaces

   Identifying the opposite end surfaces of S_1 is a prerequisite to de ning the beginning and ending points of the wireframe representation of the frame member (step 3) and creating the cross-section (step 4). To identify the opposite end surfaces of S_1, rst, all polygons of S_1 whose normal vectors are perpendicular to the direction of the neutral axis line L_1 are disregarded. The rst end surface, S_3, is formed from

the remaining polygons of S_1 whose normal vectors form an angle with line L_1 that is between 0 and 90. The second end surface, S_4, is formed from the remaining polygons of S_1 whose normal vectors form an angle with line L_1 that is between 90 and 180. For the example beam shown in Figure IV.23d, the first end surface S_3 is composed of eight polygons whose normal vectors form a 0 angle with line L_1. Conversely, surface S_4 is a mirror image of S_3 and is composed of eight polygons whose normal vectors form a 180 angle with line L_1. The wireframe of the frame member is defined as a line, L_2, whose beginning and ending points correspond to the centroids of S_3 and S_4, respectively. In the exceptional case where an end surface of S_1 has an irregular shape, which can occur for coped beam ends in the IFC4 RV as shown in Figure IV.24a, the procedure for steps 1-3 is still applicable but with the added step of consolidating the polygons into a flat surface, as shown for the surface S_3 in Figure IV.24b.

4. Creating 2D Cross-Section

   Transforming the 3D end surface, S_3, identified in step 3, into a 2D surface, S_5, is a pre-requisite for classifying the shape of the section (step 5) and measuring the section dimensions (step 6). Figure IV.23e shows the 2D transformation, S_5, of the 3D surface, S_3, of the example beam. For prismatic beams, end surfaces S_3 or S_4 can be valid surfaces to choose for representing the 2D cross-section.

5. Classifying the Shape of the Section

   Classifying the shape of the frame member cross-section, represented by surface S_5, is a prerequisite to identifying what parameters define the IFC representation of the section, IfcParameterizedProfileDef, as well as determining the orientation of the frame member in 3D space. Figure IV.25 shows the seven possible shape classifications: I-Shape, C-Shape, T-Shape v1, T-Shape v2, L-Shape, Solid-Shape, and Hollow-Shape. Each shape classification corresponds to an IfcParameterizedProfileDef used for defining the shape of the frame member

section for representation in IFC4 SAV, as shown in Table IV.15. The possible shape classi cations are represented as 3x3 grid images where each pixel corresponds to a binary value of 0 or 1. The grid images can be further deconstructed into vector arrays containing 9 elements. For example, the I-Shape grid image in Figure IV.25a can be deconstructed into a vector containing the following ordered values: 1, 1, 1, 0, 1, 0, 1, 1, 1. Similarly, the 2D surface of the cross-section of the frame member, surface S_5, can also be represented as a 3x3 grid image, as shown in Figure IV.23f. The values of the pixels in Figure IV.23f are determined by whether a polygon of S_5 is present within that pixel, i.e., the pixel value is 0 (red) if no polygon is present or the pixel value is 1 (green) if a polygon is present. The presence of a polygon within a grid pixel is determined using the Separating Axis Theorem (SAT) for determining 2D polygon collision [84]. The SAT states that if two convex polygons are not colliding, a separating line can be placed between them, as shown in Figure IV.26 [85]. Finally, the image vector of surface S_5 is compared against the preset grid image vectors in Figure IV.23f by computing the Euclidean norm of the di erence of the vectors. If the Euclidean norm is zero, then the corresponding shape of the given preset grid image vector is chosen as the shape classi cation of the section. For the cases when the shape classi cation is either Solid-Shape or Hollow-Shape, these classi cations must be more narrowly de ned as either rectangular or circular. This narrow classi cation is determined by comparing the surface area of S_5 with the surface area of an idealized rectangular or circular shape occupying an equivalent space to the polygons of S_5.

6. Measuring Section Dimensions

Measuring section dimensions is necessary for determining the parameters that de ne the shape of the frame member in IFC as well as calculating the section properties, which can also be stored in IFC. Section dimensions are identi ed

based on the beam section classi cation. For example, an IfcBeam whose section corresponds to an I-Shape would be represented in IFC4 SAV as an IfcIShapePro leDef with four de ning parameters: OverallWidth, OverallDepth, WebThickness, and FlangeThickness. See Table IV.15. Section properties, such as bending moments of inertia, torsion resistance, and cross-sectional area are determined by the measured dimensions. Figure IV.23g shows a visual representation of the measurement of the WebThickness and FlangeThickness for the I-Shape classi cation of the example beam.

7. Matching Section to O cial Designation

   Frame members can be optionally matched to their corresponding o cial designation, which provides more accurate section dimensions and properties that can replace those determined in step 6. The best matching o cial designation is found by comparing the percent di erences of the measured section dimensions to actual section dimensions listed in regional standards.

8. Identifying Material Properties

   Material properties are inferred by the material designation provided by IfcMaterial in the original IFC le. For example, if the original IfcMaterial de nes A992 Steel for the frame member object, then the o cial material properties for A992 Steel are used for the IfcMaterial de ned in the output IFC4 SAV le. If no IfcMaterial is given in the original IFC le or no standard material grade or type is recognized, then a default material of S355 Steel is applied.

9. Creating the IfcStructuralCurveMember

   The IfcStructuralCurveMember is constructed based on the spatial location of the wireframe, L_2, determined in step 3, the section information determined in steps 5-7, the orientation determined in step 5, and the material information determined in step 8. Figure IV.22b shows the nal Edge representation of the IfcStructuralCurveMember as a red line surrounded by the outline of the original

SweptSolid representation of the IfcBeam.

The following is a brief discussion about the reasoning and limitations behind the use of 3x3 grid patterns for beam shape classi cation, as utilized in Step 5 for the frame member conversion process above. The choice of a size 3x3 grid and seven patterns is used to strike a balance between accuracy and e ciency for shape classi cation. More re ned grid patterns, such as a 7x7 grid, could possibly capture discrete details, such as the curved llets of I-shapes or the rounded corners of hollow rectangular shapes. However, a more re ned grid size would necessitate de ning additional grid patterns, and the number of operations required for creating the grid images for any single beam cross-section would increase exponentially. The 3x3 grid size and the 7 grid patterns perform well on a wide range of sizes for common beam shapes in the AISC standard. However, the current procedure does not capture any shape outside of these 7 patterns well. For example, the non-prismatic shapes of steel bar joists are currently not compatible with the current frame member conversion procedure.

(a) Step 1 - Geometry Processing

(b) Step 2a - Inferring the Neutral Axis Direction

(c) Step 2b - Inferring the Neutral Axis Direction

(d) Step 3 - Identifying Opposite End Surfaces

(e) Step 4 - Creating 2D Cross Section

(f) Step 5 - Classifying the Shape of the Section

(g) Step 6 - Measuring Section Dimensions

Figure IV.23: Frame Member Conversion Steps for Obtaining Geometric and Section Information

(a) Irregular IfcBeam from ArchiCAD SO ce IFC4 RV File

(b) Step 3 for Irregular Beam Conversion

Figure IV.24: Frame Member Conversion Special Case Irregular Beam Ends

(a) I-Shape

(b) C-Shape

(c) T-Shape v1

(d) T-Shape v2

(e) L-Shape

(f) Solid-Shape

(g) Hollow-Shape

Figure IV.25: Grid Images for Common Beam Sections

Figure IV.26: Separating Axis Theorem [85]

Table IV.15: Section Shape Classi cations and Corresponding IfcParameterizedPro leDefs

Section Shape Classi cation	Corresponding IfcParameterizedPro leDef	Dimension Parameters
I-Shape	IfcIShapePro leDef	OverallWidth, OverallDepth, WebThickness, FlangeThickness
C-Shape	IfcUShapePro leDef	Depth, FlangeWidth, WebThickness, FlangeThickness
T-Shape v1	IfcTShapePro leDef	Depth, FlangeWidth, WebThickness, FlangeThickness
T-Shape v2	IfcTShapePro leDef	Depth, FlangeWidth, WebThickness, FlangeThickness
L-Shape	IfcLShapePro leDef	Depth, Width, Thickness
Solid-Shape	IfcRectanglePro leDef	XDim, YDim
	IfcCirclePro leDef	Radius
Hollow-Shape	IfcRectangleHollowPro leDef	XDim, YDim, WallThickness
	IfcCircleHollowPro leDef	Radius, WallThickness

IV.4.2 Conversion of Slabs and Walls to Structural Elements

This subsection describes the interpretation mechanism used to convert the IFC architectural model representation of slabs and walls (i.e., IfcSlab and IfcWall) to their equivalent IFC structural model representation (i.e., IfcStructuralSurfaceMember(s)). Refer to Table IV.13 for de nitions of these IFC entities. Figure IV.27 shows an example of the conversion of an IfcSlab with SweptSolid representation within an IFC4 RV le to an arrangement of IfcStructuralSurfaceMembers with Edge representations within a new IFC4 SAV le. The IfcSlab originates from the AuthorLargeStructure IFC4 RV model described in Section IV.2. Table IV.16 summarizes the input and output of the conversion process.

(a) Original IfcSlab from IFC4 RV (b) Converted IfcStructuralSurfaceMembers for IFC4 SAV [a]

Figure IV.27: Slab/Wall Conversion IfcSlab to IfcStructuralSurfaceMembers for AuthorLargeStructure Top Slab

[a] IfcEdges of the IfcFace representations of the IfcStructuralSurfaceMembers shown in red. Outline of original IfcSlab SweptSolid also shown for visual reference.

Table IV.16: Structural Slab/Wall Conversion IfcSlab to IfcStructuralSurfaceMembers

Property	Original IFC4 RV Representation	Converted IFC4 SAV Representation
IFC Class	IfcSlab	IfcStructuralSurfaceMember
RepresentationType	SweptSolid	Face
Thickness (mm)	200	200
Material	C30/37 Concrete	C30/37 Concrete
No. of Elements	1	12

The following numbered list summarizes the steps of the slab/wall conversion process. Figure IV.28 graphically represents several of the steps by using an IfcSlab from

the AuthorLargeStructure model as an example.

1. Geometry Processing

   Using the geometry processor of IfcOpenShell-Python [81], the geometry of the original IfcSlab, shown in Figure IV.27a, is processed into a tessellation of surface polygons, S_1, shown in Figure IV.28a.

2. Identifying the Largest Surface

   The largest surface of S_1, designated S_2, is determined by finding all polygons that are co-planar with the largest polygon of S_1. Figure IV.28b highlights in yellow the largest surface of the example IfcSlab. The largest surface S_2 is used to define the extent of the final triangular tessellation of the IfcStructuralSurfaceMember representation of the IfcSlab in step 5.

3. Identifying the Edge Lines

   The edge lines that define the enclosures of the outer perimeter and inner perforations of S_2 are used to create a new preliminary triangular tessellation S_3 in step 4, which is modified to form the final triangular tessellation S_4 in step 5. For example, an IfcSlab with one perforation will have two closed circuits of edge lines: one set of lines that define the perimeter, and one set of lines that define the inner perforation. However, in the example shown in Figure IV.28c, there are no perforations, so there is only one circuit of six edge lines, shown as thick black lines, that define the perimeter of S_2, highlighted again in yellow.

4. Create New Surface Based on Edge Lines

   Using the Delaunay tessellation algorithm [86], the vertices of the edge lines from step 3 create a new preliminary triangular tessellation S_3, which is modified to form the final triangular tessellation S_4 in step 5. Figure IV.28d shows the new preliminary triangular tessellation for the example IfcSlab.

5. Remove Polygons of Voids

   For IfcSlab or IfcWall elements that are concave in shape and/or contain

perforations, there will be polygons in S_3 from step 4 corresponding to voids that need to be removed. By comparing surfaces S_2 and S_3 using polygon collision detection methods [84], the polygons in S_3 corresponding to voids can be identi ed and removed to form the nal triangular tessellation S_4. Figure IV.28e shows the polygons corresponding to voids highlighted in red and the remaining polygons corresponding to S_4 highlighted in green.

6. Divide Triangles into Quadrilaterals

   Quadrilateral shell nite elements produce more accurate results than triangular shell nite elements for structural analysis software. Therefore, the triangular tessellation S_4 from step 5 is divided into quadrilateral elements that form the surface S_5. Figure IV.28f shows the quadrilateral tessellation for the example IfcSlab.

7. Determine the Thickness

   The thickness of the IfcSlab/IfcWall is determined by taking the shortest distance from the plane of the largest surface S_2, highlighted in yellow in Figure IV.28b, to the centroid point of surface S_1, shown as a black diamond-shaped point in Figure IV.28a and Figure IV.28b, and multiplying the value by two.

8. Identifying Material Properties

   Material properties are inferred by the material designation provided by IfcMaterial in the original IFC le. For example, if the original IfcMaterial de nes 4000psi Concrete for the slab or wall object, then the o cial material properties for 4000psi Concrete are used for the IfcMaterial de ned in the output IFC4 SAV le. If no IfcMaterial is given in the original IFC le or no standard material grade or type is recognized, then a default material C30/37 Concrete is applied.

9. Creating the IfcStructuralSurfaceMembers

   The geometry of the nal IfcStructuralSurfaceMembers is de ned by projecting the quadrilateral polygons of S_5 from step 6 onto the mid-plane of S_1. The

mid-plane of S_1 is de ned as a plane whose surface normal vector is equivalent to the surface normal vector of S_2 and that contains the centroid point of S_1. Figure IV.27b shows the nal IfcStructuralSurfaceMembers residing within the mid-plane of the original example IfcSlab. The thickness and material properties of each IfcStructuralSurfaceMember are determined in steps 7 and 8, respectively.

(a) Step 1 - Geometry Processing

(b) Step 2 - Identifying the Largest Surface

(c) Step 3 - Identifying the Edge Lines

(d) Step 4 - Create New Surface Based on Edge Lines

(e) Step 5 - Remove Polygons of Voids

(f) Step 6 - Divide Triangles into Quadrilaterals

Figure IV.28: Structural IfcSlab/IfcWall Conversion Steps for Obtaining Geometric and Thickness Information

IV.4.3 Element Connectivity Adjustment of Frame Members

This subsection describes the post-conversion modi cation mechanism used to adjust the spatial locations of the nodes of neighboring IfcStructuralCurveMembers of converted frame members (i.e., IfcBeams, IfcColumns, IfcMembers) so that their nodes are merged, ensuring that the structural analysis model of the output IFC4 SAV le is stable and satis es load paths. For example, Figure IV.30 shows the states of the converted AuthorLargeStructure IFC4 SAV le before (Figure IV.30a) and after (Figure IV.30c) the element connectivity adjustment of the structural frame members. Figure IV.31 shows the e ects of the element connectivity adjustment more clearly for a particular beam-column joint. The process of adjusting the connectivity of frame member nodes can be abstracted as a process of snapping the end node of a frame member to the linear wireframe body of another. When snapping occurs, the frame member that is "snapped to" is split into two linear elements at the snapping location, thereby creating an extra node at the interface of the newly connected frame members.

Sets of structural framing are sequentially snapped together according to the hierarchical order of their load paths. The IfcStructrualCurveMembers of two frame members are snapped together only if the distance between one of the wireframe endpoints of the snapping frame member and the wireframe body of the other non-snapping member is less than the allowable snapping distance $_{allowable}$, as shown by the condition de ned in Equation (IV.1).

$$_{allowable} \quad 0 \qquad \text{(IV.1)}$$

Figure IV.29 shows a simpli ed graphical representation of a hypothetical snapping action between the vectorized endpoint p_3, of a snapping frame member and the vectorized endpoints, p_1 and p_2, of the wireframe body of a non-snapping frame member. The

distance to the closest vectorized snapping point $\vec{p}_4$, is given by Equation (IV.2). The closest vectorized snapping point $\vec{p}_4$, the scalar parameter t, and the unit vector $\hat{p}$ of the line segment of the wireframe are given by Equation (IV.3), Equation (IV.4), and Equation (IV.5), respectively.

Figure IV.29: Point Snapping to Line Segment

$$= \| \vec{p}_4 - \vec{p}_3 \| \tag{IV.2}$$

$$\vec{p}_4 = \begin{cases} \vec{p}_1 & \text{if } t < 0 \\ \vec{p}_2 & \text{if } t > \| \vec{p}_2 - \vec{p}_1 \| \\ \vec{p}_1 + t\hat{p} & \text{otherwise} \end{cases} \tag{IV.3}$$

$$t = (\vec{p}_3 - \vec{p}_1) \cdot \hat{p} \tag{IV.4}$$

$$\hat{p} = \frac{\vec{p}_2 - \vec{p}_1}{\| \vec{p}_2 - \vec{p}_1 \|} \tag{IV.5}$$

$_{allowable}$ is set according to the value of the maximum cross-section dimension between the two members. For example, a shallow joist resting atop a deep girder would snap into the body of the girder below, as seen in Figure IV.31b and Figure IV.31d. There are three rounds of frame member snapping, as outlined below:

1. The rst round of snapping is between vertical IfcStructuralCurveMembers (i.e., converted IfcColumns) and horizontal IfcStructuralCurveMembers (i.e., converted IfcBeams), whereby the endpoint nodes of the horizontal members are snapped to the bodies of nearby vertical members. Therefore, the spatial location of the nodes for the snapping horizontal members is modi ed, but the spatial location of the nodes for the non-snapping vertical members remains the same. At the end of all individual instances of snapping, the endpoints of all horizontal members are adjusted to the same elevation, which enables an amenable topology for the future snapping of structural slabs to the oor beam system. Figure IV.32 highlights in red the vertical and horizontal members active in the rst round of snapping for the AuthorLargeStructure model.
2. The second round of snapping follows the same procedure as the rst round between vertical and horizontal members, except the snapping members are classi ed as joists and the non-snapping members are classi ed as girders. Joists are de ned as those horizontal members in the rst round of snapping that did not snap to any vertical member, whereas girders are de ned as those horizontal members whose endpoints did snap to vertical members. Figure IV.33 highlights in red the joist and girder members active in the second round of snapping for the AuthorLargeStructure model.
3. The third round of snapping follows the same procedures as the previous rounds of snapping, except that the snapping members are classi ed as diagonal members, the non-snapping members are classi ed as vertical members, and there is no equalization of elevation for the snapping members. The AuthorLargeStructure

model contains no diagonal members, so there is no follow-up gure to Figure IV.33.

The following brie y discusses the rami cations of snapping linear elements together for connectivity instead of other methods, such as rigid links or linear spring elements. The current procedure extends the length of linear elements to establish connections and assumes rigid frame connectivity at nodes. This modeling practice creates simpli ed "ball-and-stick" analytical models that contain a minimal number of elements, but the extension of the length of members may introduce unwanted exibility and mass to the structure. An alternative modeling practice could be the use of rigid links, which would avoid adding unwanted exibility and mass but could also introduce more sti ness than desired. Introducing linear spring elements as the connection interface between linear elements would allow for the ne-tuning of sti ness parameters by the structural engineer in order to better approximate the proper sti ness values of connections. IFC4 does not have a class for rigid links, but exible springs may be able to be represented by the IfcBoundaryEdgeCondition class.

(a) IFC4 SAV Before Frame Snapping

(b) IFC4 RV [a] Before Frame Snapping

(c) IFC4 SAV After Frame Snapping

(d) IFC4 RV [a] After Frame Snapping

Figure IV.30: IFC Files Showing Before and After Slab-to-Beam Snapping for the AuthorLargeStructure Model

[a] Architectural representation of the IFC4 SAV output, used for visual reference only. Only the IFC4 SAV le is used for vertical interoperability.

(a) IFC4 SAV Before Frame Snapping, Zoomed-In

(b) IFC4 RV [a] Before Frame Snapping, Zoomed-In

(c) IFC4 SAV After Frame Snapping, Zoomed-In

(d) IFC4 RV [a] After Frame Snapping, Zoomed-In

Figure IV.31: IFC Files Showing Before and After Structural Framing Snapping for the AuthorLargeStructure Model, Zoomed-In View

[a] Architectural representation of the IFC4 SAV output, used for visual reference only. Only the IFC4 SAV le is used for vertical interoperability.

(a) Vertical Members (before snapping) (b) Horizontal Members (before snapping)

Figure IV.32: First Round of Structural Framing Snapping Snap Horizontal Members (IfcBeam's) to Vertical Members (IfcColumn's)

(a) Girder Members (before snapping) (b) Joist Members (before snapping)

Figure IV.33: Second Round of Structural Framing Snapping Snap Joist Members[a] to Girder Members[a]

[a] Subset of horizontals from rst round of snapping

IV.4.4 Element Connectivity Adjustment of Slabs and Floor Beam Systems

This subsection describes the post-conversion modi cation mechanism used to adjust the spatial locations of the nodes of fcStructuralSurfaceMembers of converted IfcSlabs and neighboring IfcStructuralCurveMembers of converted IfcBeams. For example, Figure IV.34 shows the states of the converted AuthorLargeStructure IFC4 SAV le before (Figure IV.34a) and after (Figure IV.34c) the element connectivity adjustment, or snapping, of the slabs to the oor beams. The steps to snap IfcStructuralSurfaceMembers of a given converted IfcSlab to neighboring IfcStructuralCurveMembers of converted IfcBeams are outlined below. Several steps are graphically represented by Figure IV.35, which shows the process of the top slab of the converted IFC4 SAV le of the AuthorLargeStructure model snapping to the adjacent oor beam system.

1. Gathering Original Elements of the Slab

   The original IfcStructuralSurfaceMembers of the converted IfcSlab are gathered, and the arrangement of their quadrilateral polygons is designated as surface S_1. The geometry of S_1 will be manipulated and adjusted by the arrangement of neighboring oor beams, resulting in a new tessellation of quadrilateral IfcStructuralSurfaceMembers whose edges are compatible with the edges of the wireframes of the IfcStructuralCurveMembers of the oor beams, as shown in the nal step 8. Figure IV.35a shows surface S_1 of the converted top slab of the AuthorLargeStructure model.

2. Identifying Nearby Floor Beams

   IfcStructuralCurveMembers of neighboring oor beams are identi ed by those members whose endpoints are within a distance no more than three times the length of the slab thickness and whose endpoint coordinates fall within the domain of the planar x- and y-coordinates of the slab. Figure IV.35b shows seven

IfcStructuralCurveMembers of converted oor beams that satisfy the aforementioned proximity criteria.

3. Projecting the Original Slab onto the Plane of the Floor Beams

   Surface $S_1^{`}$ is created by projecting $S_1$ onto the plane of co-planar oor beams below, as shown in Figure IV.35c. Surface $S_1^{`}$ will be used to identify locations for the division of oor beams (step 4), create the preliminary version S_2, of the nal tessellation (step 5), and create a group of polygons corresponding to voids, V_1 (step 6), that will be useful for identifying and removing voids (step 7) from the preliminary version of the nal tessellation, S_2 into $S_2^{`}$.

4. Dividing Floor Beams Near Perimeter Points of the Slab

   IfcStructuralCurveMembers of neighboring oor beams are divided near to perimeter points of surface $S_1^{`}$, as shown in Figure IV.35d. This division makes the edges of the IfcStructuralCurveMembers more compatible with the edges of the IfcStructuralSurfaceMembers.

5. Creating The Preliminary Version of the Final Tessellation

   The preliminary version, S_2, of the nal tessellation is created by Delaunay tessellation [36] of the nodes of the divided oor beams from step 4 and the perimeter nodes of $S_1^{`}$, as shown in Figure IV.35e.

6. Creating a Tessellation Used to Identify Voids

   For the case where a slab contains voids from concavities and/or perforations, there are polygons in S_2 that need to be identi ed as voids and removed. The surface S_3 is created by Delaunay tessellation [36] of only the perimeter nodes of $S_1^{`}$, as shown in Figure IV.35f. The surface S_3 is used to identify a key group of polygons corresponding to voids as explained in step 7.

7. Identifying Group of Polygons Corresponding to Slab Voids

   The polygons of S_3 that correspond to slab voids are identi ed by comparing the polygons of surface S_3 with the polygons of surface $S_1^{`}$. Polygons of S_3 that are

outside the bounds of surface $S_1^{`}$ are labeled as a group of voids V_1, highlighted in red in Figure IV.35g.

8. Remove Voids from the Preliminary Tessellation

   The group of voids from step 7, V_1, are used to identify the polygons in S_2 that also correspond to voids, highlighted in green in Figure IV.35h. The remaining polygons, highlighted in red, constitute the updated surface, $S_2^{`}$

9. Divide Triangles into Quadrilaterals for the Final Tessellation

   The triangular tessellation of $S_2^{`}$ is divided into a nal quadrilateral tessellation, $S_2^{\backslash}$, as shown in Figure IV.35i. This nal quadrilateral tessellation de nes the new geometry for the IfcStructuralSurfaceMembers of the slab.

10. Bisection of Floor Beams

    The edges of the slab tessellation were bisected in step 9 to form quadrilateral shapes, so the edges of the IfcStructuralCurveMembers of the neighboring oor beams are bisected as well, ensuring that all edges and nodes of the various IfcStructuralSurfaceMembers and IfcStructuralCurveMembers satisfy connectivity and compatibility requirements for nite element meshing in structural analysis software.

The following is a short discussion about the modeling practices and assumptions for the connectivity adjustment procedure above. The slab and oor beams are modeled as a composite system where the e ective neutral axes of all the beam and slab connections are assumed to act at the centroid of the slab. Therefore, the neutral axes of the beams and slab are projected onto a common horizontal plane. For the procedure described above, this common horizontal plane is the horizontal plane containing the linear representations of the beam centerlines below the slab. Therefore, the neutral axis of the oor slab is projected downward onto the oor beam system. However, future versions of this modeling procedure will instead project the oor beams upwards to the plane of the oor slab, thereby following more closely to industry practice.

(a) IFC4 SAV Before Slab-to-Beam Snapping

(b) IFC4 RV [a] Before Slab-to-Beam Snapping

(c) IFC4 SAV After Slab-to-Beam Snapping

(d) IFC4 RV [a] After Slab-to-Beam Snapping

Figure IV.34: IFC Files Showing Before and After Slab-to-Beam Snapping for the AuthorLargeStructure Model

[a] Architectural representation of the IFC4 SAV output, used for visual reference only. Only the IFC4 SAV le is used for vertical interoperability.