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# AUTOMATION IN DIGITAL ENGINEERING SOLUTIONS FOR NUCLEAR DESIGN-CONSTRUCTION INTEGRATION USING FEM-BIM INTEROPERABILITY

**Harleen Kaur Sandhu[1], William Ashe[2], Nicholas Crowder[3], Abhinav Gupta[4], and Kevin Han[5]**

[1]Postdoctoral Research Scholar, CNEFS, North Carolina State University, USA (hksandhu@ncsu.edu)
[2]Graduate Student, CNEFS, NCSU, USA
[3]Graduate Student, CNEFS, NCSU, USA
[4]Director, Center for Nuclear Energy Facilities and Structures (CNEFS), NCSU, USA
[5]Associate Professor, CNEFS, NCSU, USA

## ABSTRACT

Design changes during the construction phase of nuclear power plants can lead to significant financial expenses and delays in the project schedule. Effective communication and management of these changes with all involved parties to assess the associated risks effectively can potentially prevent cost overruns and delays. Enhancing the interoperability between building information modeling (BIM) and finite element (FE) analysis tools can mitigate the impacts of redesign through efficient communication between design and construction teams. This improvement involves creating an FE model for structural elements or mechanical piping systems based on BIM's building data. Identifying the geometric location and section properties of BIM elements is essential for this process. Hence, this study provides an overview of an interoperability program between BIM and FEM, facilitating the seamless integration of efforts by design and construction engineers to ensure alignment across different project components. The extracted structural properties are utilized to generate accurate geometric and structural FE models in ANSYS Mechanical APDL. Prior to approving design changes due to construction constraints, a thorough structural analysis must be conducted. This research explores automated structural analysis of nuclear systems using an updated FEM model, emphasizing standardized interfaces for software communication. Improved interoperability and automated FE analysis facilitate seamless information flow between design and construction engineers and enable risk-informed construction management.

## INTRODUCTION

Construction of nuclear power plants is a complex and time-consuming process, with many different teams working on various aspects of the project. Delays in scheduling and increases in associated costs can adversely affect the construction of new plants. Prime examples of these issues are highlighted in the construction of the VC Summer Nuclear Station in Jenkinsville, South Carolina as well as the Olkiluoto Nuclear Power Plant project in Finland. In both cases, actual costs were well above projected costs, causing the projects to be delayed (Crees, 2018; Greene and Tickell, 2015). One key reason for construction cost escalations and schedule delays is related to on-site design changes needed during construction. A delay in the construction schedule while awaiting design change approvals leads to cost escalations. The nuclear industry is actively developing modular designs to reduce construction schedules and costs. However, stringent quality requirements can create tremendous problems in modular construction without a mechanism to accept some of the construction deviations in the manufacturing of modules especially in the context of excessively conservative requirements for construction tolerances.

Finite Element Modeling (FEM) and Building Information Modeling (BIM) software are used in the design and construction of nuclear power plants. FEM software, such as ANSYS or ABAQUS, is used

in the design process to analyze the stresses and strains in a structure, while BIM software, such as AVEVA E3D or Revit, is used to manage and coordinate the different aspects of on-site construction. BIM establishes a collaborative digital repository where all stakeholders in Architecture, Engineering, and Construction (AEC) can store and share pertinent information relating to the project, throughout the lifecycle of construction. Interoperability is a crucial aspect of the BIM process which facilitates the seamless exchange of data across various domains (Sacks et al., 2018). A digitized design environment involving architects and structural engineers requires the capability for data interchange between BIM and FEM software. Efficiency enhancement, cost reduction, and elevation of the quality and performance of building construction can be achieved through the use of BIMF-FEM interoperability programs (Cerovsek, 2011).

Nevertheless, as indicated by a McGraw Hill industry survey, while structural analysis ranks highest in frequency index—reflecting its frequent use with BIM processes—it exhibits the second-lowest value/difficulty ratio among industrial professionals (Construction, 2014). This means that there is a substantial need for BIM interoperability in structural analysis, yet its current implementation is inefficient for industry standards. Presently, the model-based data exchange between BIM-based software in the BIM and FEM domains lacks full interoperability, leading to data loss and necessitating extensive remodeling effort (Gerbino et al., 2021). The existing methods intended for BIM interoperability in the context of structural analysis confront substantial technical hurdles, including issues like joint disconnections, element embedment, element overlapping, and missing critical information (Muller et al., 2017). To address this gap, there is a need to establish a framework for facilitating interoperability between BIM and structural analysis software while ensuring that essential structural data remains intact. This requirement extends to both primary structural building systems and secondary non-structural systems, such as equipment and piping. A previous study (Perrone and Filiatrault, 2017) introduced an Excel-based application designed for the automatic seismic analysis of piping systems, leveraging BIM data imported using the Industry Foundation Classes (IFC) format. However, this method solely captures the geometric properties of piping, necessitating manual input of other crucial parameters, such as section properties. Similarly, another study (Crowder et al., 2022) presented a tool that interprets structural properties from IFC files exported from the CAD software Revit, but this solution focuses primarily on pipe segments, neglecting other vital piping components like elbows and valves. Efforts are needed to develop more comprehensive and standardized solutions that encompass all aspects of structural analysis for piping systems within the BIM framework, addressing the limitations of current methods.

A previously designed interoperability program between BIM and FEM, by Crowder et al. (2022), will allow design and construction engineers to efficiently integrate their work and ensure alignment between the different parts of the project. However, before approving any change in the design of the system due to construction-related constraints, structural analysis of the system has to be conducted and the results need to be investigated for accuracy (Mahanta et al., 2022; Patel et al., 2022). The implementation of quick and automated structural analyses can significantly streamline the workflow for design and construction engineers, offering time savings in the decision-making process regarding on-field design changes. Moreover, these automated digital solutions have the potential for continuous evolution and integration with the digital twin of the system. With the increasing emphasis on autonomous operations in nuclear power plants (Sandhu et al., 2023b), the incorporation of automation in the design and analysis processes becomes pivotal. This not only contributes to substantial time savings but also seamlessly aligns with the capabilities required for autonomous operations. Furthermore, the integration of automated design and analysis can be seamlessly incorporated into online condition monitoring solutions (Sandhu et al., 2023a, 2022b), enhancing the monitoring and maintenance of various structural and mechanical systems within the nuclear power plant.

This research explores automation techniques to perform structural analysis of nuclear structural and mechanical systems using the updated FEM model and checking for any discrepancies in the results.

Novel approaches to managing heterogeneous data, data integration, information assimilation, and data visualization are investigated. In addition, this research focuses on the development of standardized interfaces and protocols to allow diverse software to communicate with each other. Improvement in interoperability between any computer-aided design (CAD) and computer-aided engineering (CAE) software, along with automation of FE analysis can allow a seamless flow of information between the design and the construction engineers. It can also facilitate the development of risk-informed construction management to allow acceptance of construction deviations when stringent quality requirements like tolerances are not met.

## BIM-FEM INTEROPERABLE SOFTWARE

The Industry Foundation Classes (IFC) data schema serves as the conduit for exporting and interpreting BIM data. IFC represents a standardized data schema designed for exporting BIM model data into an open data format. A multitude of widely used architectural BIM software applications, such as Autodesk Revit, AVEVA E3D, and Graphisoft ArchiCAD, employ the IFC export format. In practical terms, the previously proposed tool (Crowder et al., 2022) harnesses innovative algorithms to automatically extract spatial location and structural cross-section information for various building and piping elements, including beams, columns, slabs, walls, pipe segments, pipe fittings, elbows, t-joints, and valves, using IFC data as its input. The acquired structural information is then stored and can be exported to either an open (IFC) or proprietary (ANSYS macro text file) data format, thereby enabling its import into diverse finite element analysis software platforms. This tool holds significant promise for improving the efficiency and accuracy of structural analysis in the context of nuclear power plant systems.

Table 1 details some commonly used BIM-based CAD software and CAE software, their parent companies, and their current versions. Two models of architectural structural and piping designs are considered to develop the CAD-to-CAE one-way interoperability tests, as illustrated by their BIM models in Figure 1. Table 2 lists the two models (Simple Structure and Pipe System) and their authoring software, along with a third application case study (Large Structure) to test the effectiveness of the proposed automation program. The models are exported to IFC files using the IFC export functionality of the CAD software. The flowchart for the IFC model to FEM model conversion process is shown in Figure 2, where each step of the process is mentioned sequentially. The final converted FE models are shown in Figure 3, as visualized in ANSYS Mechanical APDL.

Table 1: Commonly used CAD and CAE Software

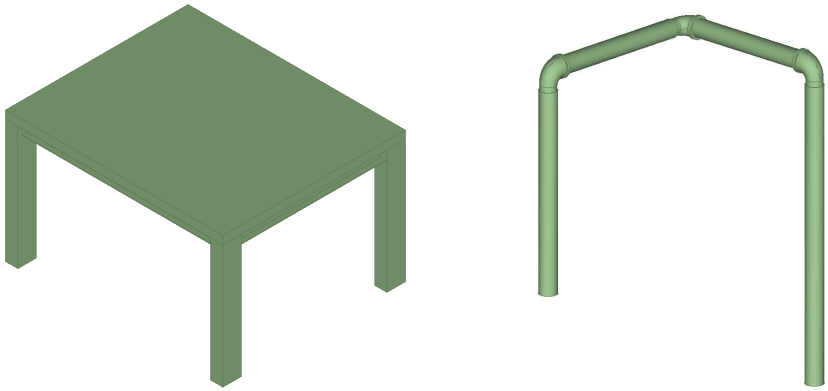
| Platform | Company | Software | Version |
|---|---|---|---|
| Computer Aided Design | Autodesk | Revit | 2024 |
| | AVEVA | E3D Design | 3.1.3.0 |
| Computer Aided Engineering | CSI | SAP2000 | 23.0.0 |
| | ANSYS | Mechanical APDL | 2022 R2 |

## AUTOMATION FOR STRUCTURAL ANALYSIS

An existing interoperability solution (Crowder et al., 2022) established for CAD and CAE software enables design and construction engineers to seamlessly integrate their efforts, ensuring coherence across various project components. However, prior to finalizing any design alterations arising from construction-related limitations, it is important to conduct a structural analysis of the system. Implementing quick and

Table 2: Description of Case Studies

| Software | Creator | Model Name |
|---|---|---|
| IfcOpenShell | authors | Simple Structure |
| Revit | authors | Pipe System |
| IfcOpenShell | authors | Large Structure |



(a) Simple Structure (b) Piping System

Figure 1. BIM CAD Models

automated structural analyses in design and construction workflows saves time and effort. This automation, which can evolve and integrate with the system's digital twin, also enhances online condition monitoring solutions (Sandhu, 2021; Sandhu et al., 2022a,c) for improved maintenance. Despite the existence of a novel tool designed for one-way interoperability between BIM and FEM, it is essential to acknowledge and address specific limitations inherent in the tool. These limitations must be resolved before achieving any level of automation in the structural analysis of the system. Thorough consideration and mitigation of these constraints are essential steps toward optimizing the tool's functionality and ensuring its effectiveness in facilitating automated structural analysis processes. These limitations and their possible solutions are mentioned below:

- *Material Properties and Grade Strength*: When the CAD software generates IFC files, material properties may be omitted, particularly in the context of piping systems. In addition to the material properties, the grade information may also be excluded from the IFC file. Consequently, the suggested conversion tool defaults to assuming the material as S355 Steel. Alternatively, users have the option to manually input the accurate material information.

- *Finite Element Mesh*: To perform structural analysis, it is essential to mesh the finite element model. The mesh size assigned to each element plays an important role in defining the design, and the analysis results can exhibit significant variations depending on the specified mesh size values. Therefore, the user is prompted to input explicit mesh size values for elements; otherwise, a default value of 1 is automatically selected for a fundamental analysis.

- *Boundary Conditions or Constraints*: It is essential to apply boundary conditions or constraints to the model for structural analysis. These conditions include fixing the structure in all directions or allowing release in specific translational or rotational degrees of freedom. The specified boundary conditions

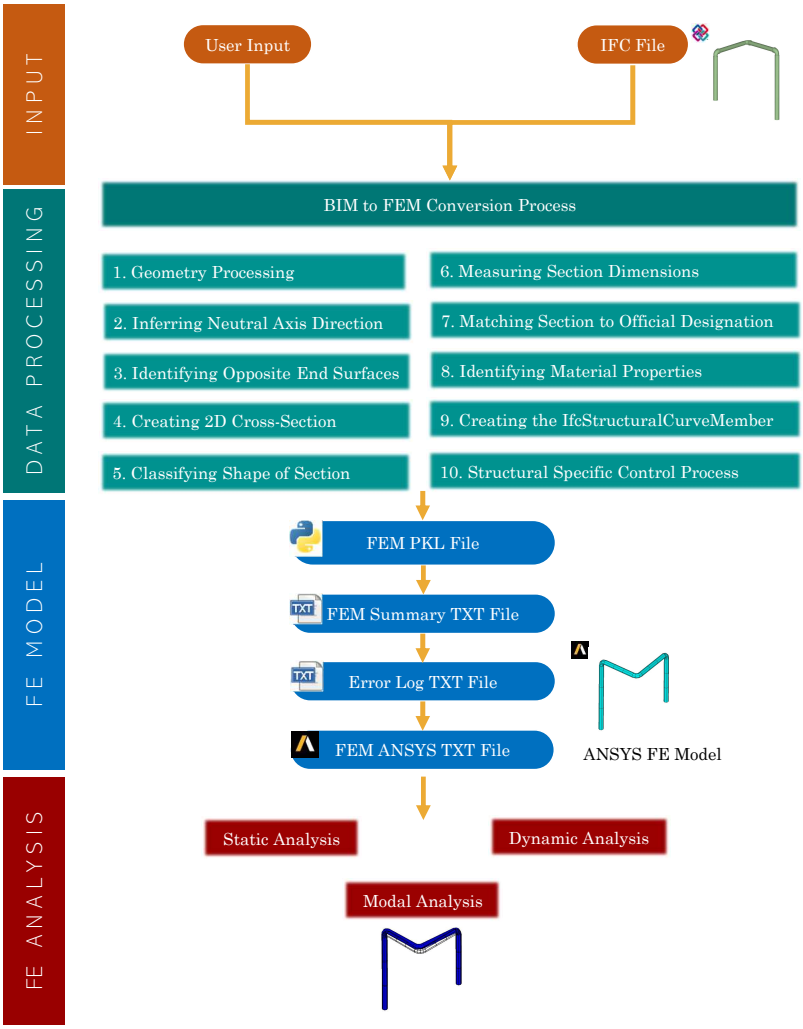
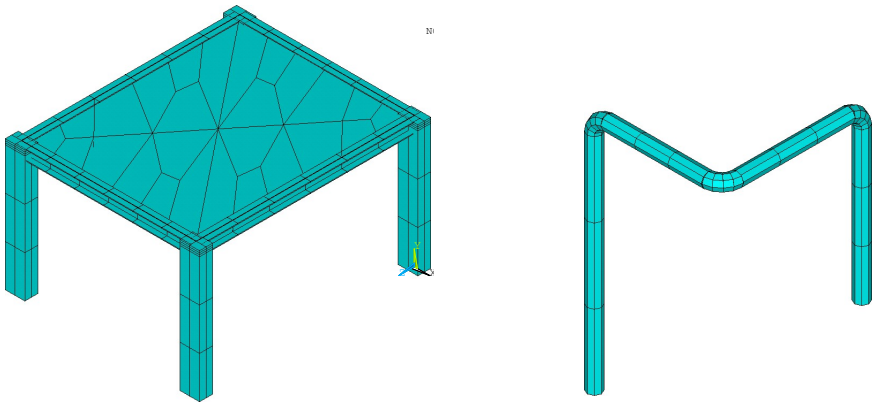



Figure 2. Workflow of the Automation Program

have a substantial impact on the outcomes of the analysis. As the IFC file lacks the capability to generate this information, the user must either input the constraints or opt for a default setting where all end nodes of the system are fixed. The user retains the flexibility to release any required degrees of freedom later, enabling a more accurate analysis.

- *Preferences for Dynamic Structural Analysis*: Structural analysis comprises various types, including static analyses for impact loads, modal analysis to determine natural frequencies and mode shapes, and dynamic analysis against earthquake loads or harmonic excitations. Depending on the user's preference, the automated solution generates the necessary finite element analysis file. As modal analysis forms the foundation for dynamic structural analysis, this paper focuses on illustrating an example of modal analysis for the considered models. When conducting modal analysis, the user is required to specify the number of modes to be extracted from the system's behavior.

After recording the limitations in the information extracted from the IFC file and incorporating user-defined preferences into the proposed automated program, the structural analysis of the system is initiated. Visualization of the FE model and the analysis results is achievable through selected CAE software. For



(a) Simple Structure (b) Piping System

Figure 3. FE CAE Models in ANSYS APDL

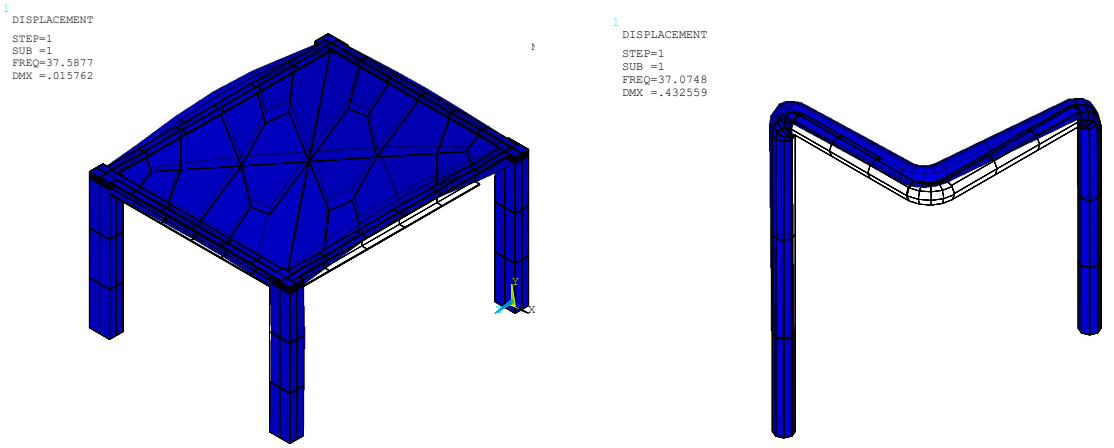
this research, ANSYS Mechanical APDL is chosen for the FE analysis of the nuclear building and piping system. The first 5 natural frequencies from the modal analysis of both systems are presented in Table 3. The first mode shape for each system is depicted in the Figure 4. The structural system model took 13 seconds from the commencement of the IFC file conversion until the generation of analysis results, while the piping system took 17 seconds.

Table 3: First 5 Natural Frequencies from Modal Analysis

| **Mode Number** | **Simple Structure** | **Pipe System** |
|---|---|---|
| 1 | 37.58 Hz | 37.07 Hz |
| 2 | 42.10 Hz | 56.09 Hz |
| 3 | 57.29 Hz | 83.39 Hz |
| 4 | 86.28 Hz | 114.49 Hz |
| 5 | 93.65 Hz | 144.04 Hz |

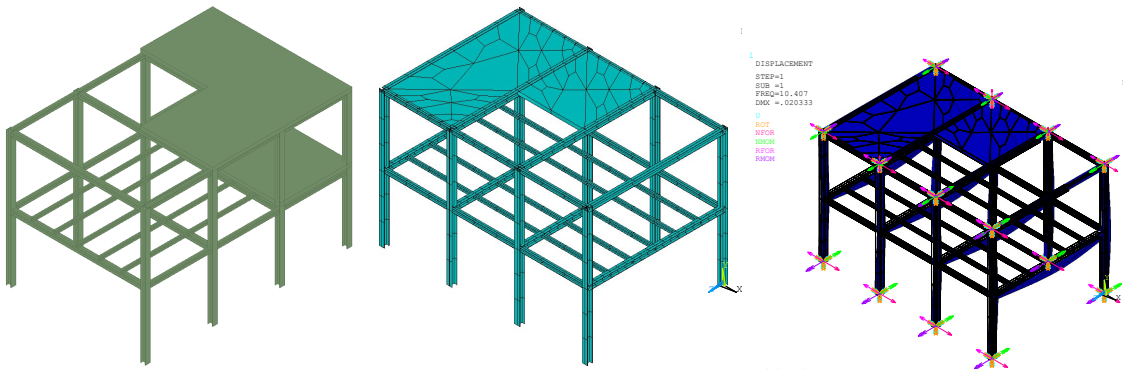
The experimental evaluation of the analysis automation program involves subjecting it to testing on a sizable structural model, as shown in Figure 5a. The testing includes the BIM-FEM conversion and the generation of modal analysis results. The proposed automated program demonstrates efficiency by completing the process in 21 seconds. The results of the BIM-FEM conversion are shown in Figure 5b, and the first mode shape is illustrated in Figure 5c.

The rapid and initial structural analysis of a system within a nuclear facility highlights the significance of the proposed automated tool. When mandatory design alterations are necessitated by on-site construction requirements, the proposed tool enables a swift conversion of BIM data to FE models, accompanied by a basic structural analysis. This capability allows construction engineers to promptly visualize the impacts of the proposed design changes. In the event of design inefficiencies or non-compliance with code requirements, the construction engineer can iteratively refine the existing design. Subsequently, the modified model can be transmitted to the structural engineer for final approval. This streamlined process minimizes the back-and-forth communication, resulting in substantial time savings, cost reduction, and enhanced efficiency in data and information exchange among various project teams.




(a) Simple Structure (b) Piping System

Figure 4. First Mode Shape




(a) BIM CAD Model (b) FE CAE Model (c) First Mode Shape

Figure 5. Large Structure BIM to FEM to Modal Analysis

## CONCLUSIONS

In the field of the Architecture, Engineering, and Construction (AEC) industry, there is an escalating demand for the digitization of model-centric data exchange within Building Information Modeling (BIM) workflows. However, users continue to grapple with challenges when it comes to exchanging data between BIM-oriented Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software, even when employing the open, non-proprietary Industry Foundation Classes (IFC) format for data exchange. Existing academic research primarily concentrates on system-level aspects of building models, with relatively limited attention directed towards the exchange of model data for piping systems. Therefore, this study extends the functionality of a previously introduced BIM interoperability tool based on the IFC standard (Crowder et al., 2022). This enhancement involves the automation of structural analysis for BIM CAD structural and mechanical-piping design models. The newly augmented tool is subjected to testing using IFC files originating from architectural designs generated within commercial CAD software. The results of this testing exhibit an enhancement in the interoperability and analysis capability between CAD and CAE systems when utilizing IFC-based data exchange, surpassing the performance of current practices. By utilizing the proposed automated tool, construction projects can benefit from accelerated

decision-making, decreased labor hours, and optimized collaboration between design and construction teams.

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