

## GEOMETRIC AND STRUCTURAL DATA EXTRACTION ALGORITHMS TO SUPPORT BIM INTEROPERABILITY BETWEEN ARCHITECTURAL AND STRUCTURAL ANALYSIS MODELS

Nicholas Crowder<sup>1</sup>, Joomyung Lee<sup>2</sup>, Kevin Han<sup>3</sup>, Abhinav Gupta<sup>4</sup>

<sup>1</sup> Doctoral Student, CCEE, North Carolina State University, USA ([nccrowde@ncsu.edu](mailto:nccrowde@ncsu.edu))

<sup>2</sup> Postdoctoral Scholar, CCEE, North Carolina State University, USA ([jlee57@ncsu.edu](mailto:jlee57@ncsu.edu))

<sup>3</sup> Assistant Professor, CCEE, North Carolina State University, USA ([khan6@ncsu.edu](mailto:khan6@ncsu.edu))

<sup>4</sup> Professor, CCEE, North Carolina State University, USA ([aguptal@ncsu.edu](mailto:aguptal@ncsu.edu))

### ABSTRACT

Design changes during construction of nuclear power plant facilities may incur exorbitant costs and schedule delays, as changes must be carefully communicated and managed with all stakeholders in order to properly assess risk. Re-design impacts can be reduced by improving the interoperability between building information modeling (BIM) and finite element (FE) analysis tools, which would help the communication efficiency problem between designer groups and construction groups. To generate an FE model of structural framing elements (i.e., load bearing beams, columns, braces, etc.) from BIM building data, the geometric location and section properties of the BIM structural elements must be identified. Therefore, this paper presents two generally applicable algorithms for the automatic extraction of the geometric location data and structural section data, respectively, of structural framing elements from BIM models. The BIM to FE conversion algorithm is developed and tested on two case studies: (1) Individual AISC steel beams in Autodesk Revit and (2) Primary structural framing for a sample building in AVEVA E3D, whereby the extracted structural properties are used to generate geometrically and structurally accurate FE models in ANSYS Mechanical APDL.

### INTRODUCTION

Design changes during construction projects can result in increased costs and schedule delays. According to Adams (2014) and Proctor (2021), in recent nuclear construction projects, the construction delays and costs were led by redesigns requiring regulatory approval, which is a common pattern negatively affecting vendors and customers in the nuclear industry. Chang (2002) discusses how various controllable and uncontrollable factors from field work impose challenges to time schedules. Aslam et al. (2019) and Han et al. (2013) claim that isolated design work from the construction phase necessarily gives rise to design changes and ensuing cost overruns and delays. Reducing the influences of not only the time delay but also assessment of the updated risks due to design changes is the key to improving engineering workflows. For this reason, there is an increased demand for the improvement of virtual engineering workflows through interoperability between building information modeling (BIM) and finite element (FE) analysis tools. However, there is currently no standardized process for a seamless data exchange between BIM architectural design and structural analysis models. Existing methods for BIM interoperability for structural analysis face technical challenges, such as joint disconnection, element embedment, element overlapping, and missing information (Muller et al. 2017).

## ***Objective***

To facilitate interoperability between BIM and structural analysis tools without loss of necessary structural information, this paper presents two algorithms for the automatic extraction of the geometric location information and structural section information, respectively, of structural framing elements from BIM models. The IFC data schema is used as a vehicle for exportation and interpretation of BIM data. The BIM to FE conversion algorithms are incorporated into a BIM interoperability tool that automatically exports the extracted structural data to a text file containing macros for generating a structural model in the finite element analysis software ANSYS Mechanical APDL. The algorithms are developed and tested on frame members in both Autodesk Revit and AVEVA E3D.

## **BACKGROUND: BIM INTEROPERABILITY AND IFC**

Researchers have noted several types of challenges encountered when implementing solutions for BIM interoperability to design and structural models. These include software limitations in geometric information conversion (Watson 2011; Yalcinkaya and Singh 2014; Fleming 2016), missing information and inconsistency (Sacks et al. 2010; Bank et al. 2010), and geometric complications (Muller et al. 2017). Industry Foundation Classes (IFC) is the most widely used information exchange format for BIM software (Volk et al., 2014). IFC is a standardized, vendor-neutral data schema for digital representation of the built asset industry. Because of IFC's standardization and applicability amongst many BIM platforms, IFC-based BIM interoperability has proven to be an effective method for several researchers (Wan et al. 2004, Ling et al., 2011, Wang et al., 2015, Wu et al, 2021). However, BIM export to IFC may not contain all necessary information for structural analysis (Thein 2010, Ren et al. 2018). Overall, interoperability challenges related to information have been a focus of the research community.

## **PROPOSED STRUCTURAL FRAMING CONVERSION ALGORITHMS**

To generate a finite element model of structural framing elements (i.e., load bearing beams, columns, braces, etc.) from BIM building data, the geometric, structural, and material properties of the individual elements must be identified. Geometric and structural properties can be described as:

1. Geometric Location Information (i.e., Cartesian coordinate data for the starting and ending points)
2. Structural Section Information (properties derived from cross section shape, orientation, and dimensions i.e., bending moments of inertia, area, torsion constant, warping constant, etc.)

After BIM data is exported to IFC, these necessary structural properties may not always be explicitly defined in the IFC properties of individual elements. For example, a BIM concrete column with a solid circular cross section may be exported to a solid model IfcColumn entity where the cross sectional radius is explicitly defined by IfcProfileDef and the shape extruded over a length defined by IfcExtrudedAreaSolid. However, a contrasting example could be a BIM steel girder with a more complex I-shaped cross section that is exported to a solid model IfcBeam entity where the entire 3-dimensional shape representation is composed of hundreds of triangulated facets whose vertices are defined by IfcCartesianPointList3D. In the latter example, the geometric properties of the BIM element are presently unknown, unless they are explicitly defined as user-defined attributes and exported properly to IFC. Therefore, a BIM to FE model conversion tool for structural framing should be developed for generalized compatibility with all manner of IFC shape representations, whether they are explicitly defined or not. The generalized algorithms presented in this paper aim to be applicable to any structural framing elements that are exported to IFC as IfcBeam, IfcColumn, or IfcMember elements (hereby referred to commonly as frame elements). For this research, the exported IFC elements that represent structural framing are assumed to be straight and prismatic and not have coped ends.

### ***IFC Data Preprocessing: IfcConvert***

There are many different IFC shape representations that IFC elements can assume, which makes developing a generalized process for interpreting 3D shape data difficult. Therefore, for this research, IFC data exported from BIM goes through a pre-processing phase whereby the IFC file is converted to the OBJ Wavefront .obj file format using the IfcConvert application. OBJ is a simple data format developed by Wavefront Technologies and used for representing 3D geometry through polygons defined by lists of vertices. IfcConvert is an open-source application used for converting IFC files into various data formats. Figure 1 shows IFC and OBJ representations of an I-beam BIM element from AVEVA E3D.

#### ***Algorithm #1: Inferring Geometric Location Information***

Geometric location information in the form of Cartesian coordinates for the start and end nodes of the centroidal axis of straight, prismatic structural framing elements can be inferred from the tessellated OBJ geometry of the IFC element.

The workflow steps are as follows:

1. Select a frame member.  
Compatible IFC elements are IfcBeam, IfcColumn, and IfcMember. Compile OBJ geometry data of the IFC element in the form of the various triangular polygons composed of three defined vertices each.
2. Calculate total surface area.  
The total surface area of the frame element equals the summed area of the individual OBJ polygons.
3. Calculate center of mass.  
The center of mass of the frame element can be calculated by taking the weighted average of the individual OBJ polygon centroids, whereby the assigned weight is the corresponding area of each OBJ polygon.
4. Identify the OBJ polygons that compose the two extreme co-planar polygon surface groups.  
The various triangular OBJ polygons that comprise the overall frame element shape can be categorized into different groups corresponding to common infinite planar surfaces. Of these various co-planar polygon surface groups, the two furthest surfaces from the center of mass correspond to the beginning and end sectional surfaces of the frame element.
5. Calculate centroids of the two extreme co-planar surface groups.  
The two centroids of the two extreme co-planar surface groups can be calculated using a similar weighted average approach as described in step 3. The two centroid locations correspond to the coordinates of the beginning and end nodes lying along the centroidal axis of the frame element. Figure 1 shows the result of a AISC W6x16 steel beam, where the centroidal axis is plotted as a line colored red, and the obj geometry is plotted as surfaces colored blue.

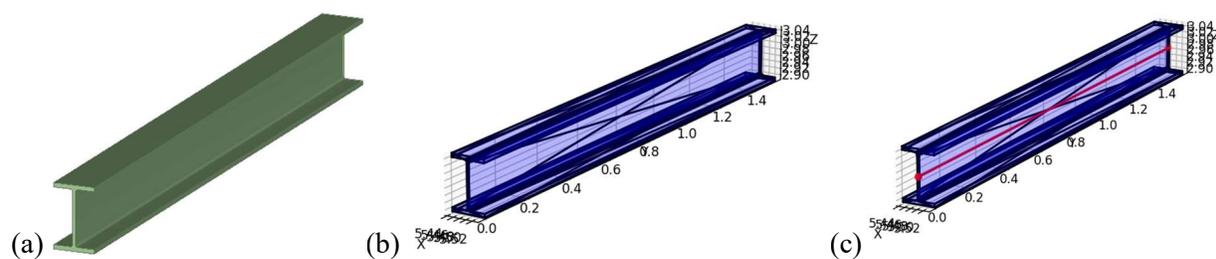


Figure 1. W6x16 IfcBeam - (a) IFC representation (b) OBJ representation (c) Centroidal axis plotted

### ***Algorithm #2: Inferring Structural Section Information***

Structural section information such as frame element cross section shape classification, orientation, and dimensions are prerequisites to calculate section properties that are required for FE structural analysis. Cross section shape classification is implemented before section property related dimension and orientation inference because the dimensions that FE model needs are determined according to the cross section shape. For example, in the case of regular rectangular shape concrete columns, only the base and height of the cross section is required to calculate area, moment of inertia, and so on. Whereas, in the case of I-beams, the required dimensions are depth, flange width, web thickness, and flange thickness. The sequentially performed algorithm is illustrated in the workflow in Figure 2.

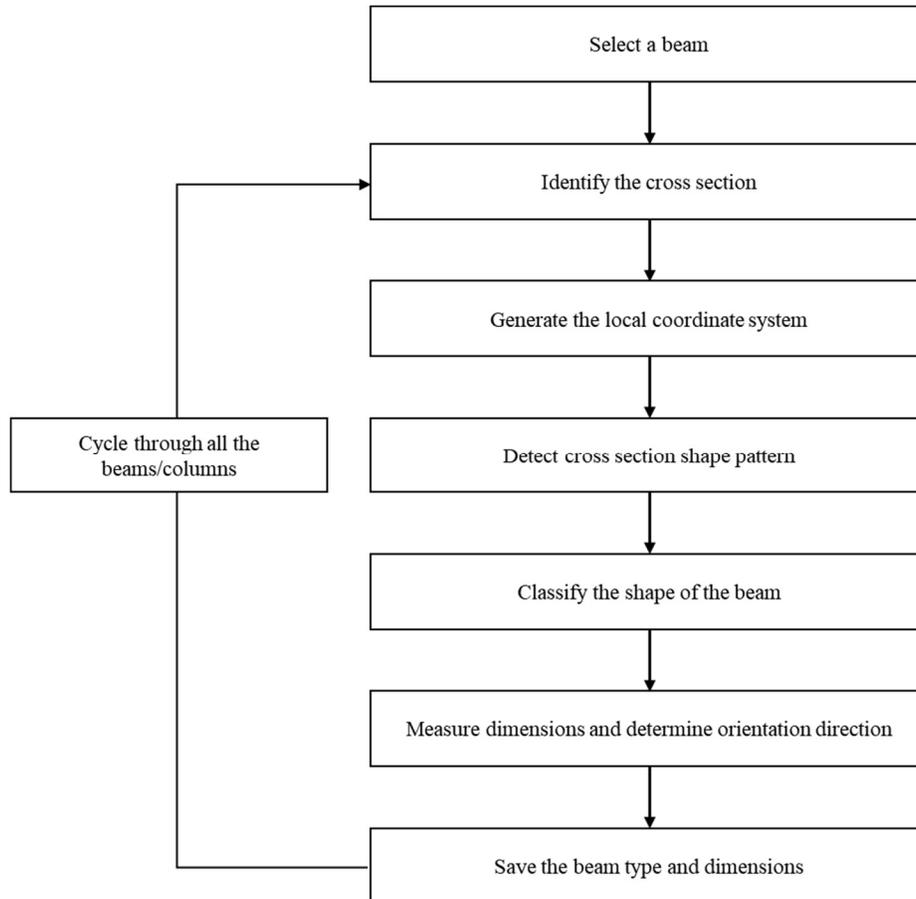


Figure 2. Flowchart for Inferring Structural Section Information

The workflows steps are as follows:

1. Select a frame member.  
Compatible IFC elements are IfcBeam, IfcColumn, and IfcMember. Compile OBJ geometry data of the IFC element in the form of the various triangular polygons composed of three defined vertices each.
2. Identify the cross-section of the selected frame element.  
See step 4 of the geometric location information algorithm. Choose one of the extreme co-planar surface groups of polygons as the representative shape for the cross section.

3. Generate the local coordinate system for locating the cross-section  
 To parse the data easily, a local coordinate system is generated virtually. The local coordinate system consists of local X-axis (red) along with the normal vector of the cross-section surface, local Z-axis (blue) along with the normal vector of the largest surface of the frame element, and local Y-axis (green), which is the cross product of the two axes. Figure 3 shows the local coordinate system view for a W6x16 IcfBeam.
4. Detect cross section shape pattern using 2D grid overlay.  
 A 6x6 2D grid is overlaid the local orientation of the cross section. The separating axis theorem, a simple algorithm for detecting polygon collisions, identifies which grid cells contain OBJ polygons of the IFC element. Grid cells are assigned binary values of 1 (polygon detection) or 0 (polygon nondetection). Figure 3 shows an example of a W6x16 IcfBeam with color-coded detection states for the 6x6 grid overlay, where green cells indicate polygon detection (value of 1) and red cells indicate polygon non-detection (value of 0).

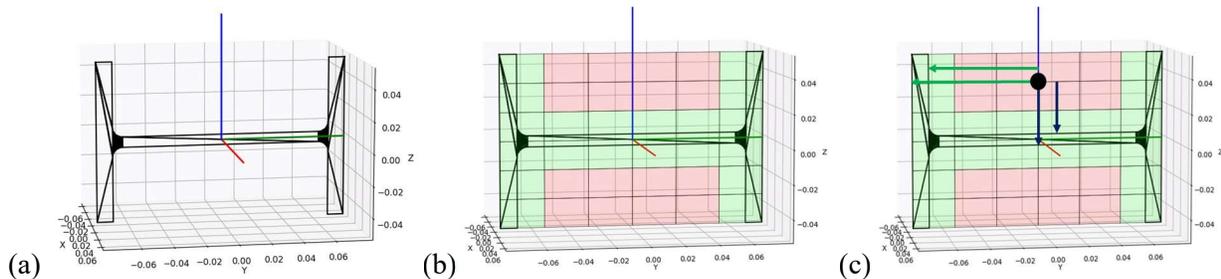
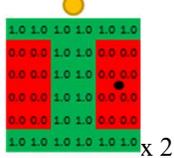
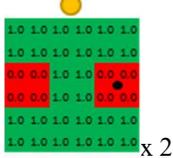
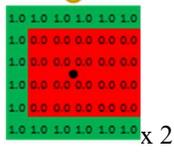
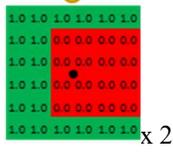
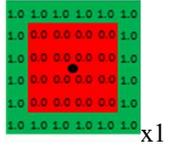
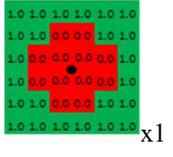
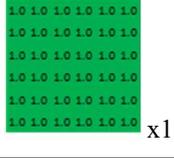


Figure 3. W6x16 IcfBeam - (a) Local cross section (b) Marked 6x6 overlay grid pattern (c) Dimension measurement from ref. point

5. Classify the shape of the cross section based on minimized error against other preset patterns.  
 Table 1 shows the preset 6x6 overlay shape patterns for some common AISC beam shapes. The 6x6 grid pattern is found to be an efficient mesh size for categorizing the various AISC shapes without adding unneeded complexity and computational cost. The 6x6 grid patterns of the presets and the marked grid from the previous step can be represented as image vectors and compared using L2 norm error, which aims to identify the difference between two vectors. Based on the L2 norm error with the 6x6 size vectors, the selected frame element's cross section shape is classified according to the corresponding preset shape. The classification algorithm covers all types of AISC standard beams including I-shape, C-shape, L-shape, T-shape, hollow shape, and solid shape. Table 1 illustrates just some select samples of presets from the AISC standard beam types.
6. Measure dimensions and determine orientation direction.  
 The required dimensions for section property calculations depend on the cross section shape. Dimensions are measured from respective reference points, as indicated by the black dots positioned on the various preset shape patterns in Table 1. For example, Figure 3c shows four vectors radiating out from the common measurement reference point. The magnitude of these four vectors are enough to calculate the basic dimensions for I-beams: flange width, flange thickness, web thickness, and depth. The orientation direction for a classified cross section corresponds to the yellow dots shown on the preset shape patterns in Table 1.
7. Save the cross section shape classification and orientation
8. Repeat the process  
 Cycle through the remaining frame member elements.

Table 1. Preset 6x6 overlay shape patterns for common AISC beam shapes

Beam Type	Version 1 (No. of rotations)	Version 2 (No. of rotations)	Version 3 (No. of rotations)
I Shape	 x 2	 x 2	
C Shape	 x 2	 x 2	
Hollow shape (rectangular or circular)	 x1	 x1	 x1
Solid (rectangular or circular)	 x1		

## CASE STUDY APPLICATION

The previous section described the procedural steps for two algorithms developed to convert IFC data of BIM elements to structural elements in a finite element tool for structural analysis. This section applies those conversion algorithms to two BIM-to-FE conversion case studies:

1. Individual AISC steel beams modeled in Autodesk Revit
2. Primary structural framing of a sample building in AVEVA E3D.

The conversion algorithms are shown to accurately classify the cross section shapes, measure the cross section dimensions, and locate the centroidal axis in Cartesian space.

### Case study #1 - Autodesk Revit AISC Beams

For the first case study, three AISC steel beams are modeled in Autodesk Revit. The three beams have shape designations of W14x730, MC8x20, and Pipe2-1/2XXS. Both of the conversion algorithms previously discussed are applied to each individual beam element. The algorithms classify the cross section shapes and infer their dimensions based solely on the 3D geometry of their IfcBeam representations. Figure 4 shows the beam elements in various stages of the conversion process beginning with BIM export to (1) IFC representation, (2) localized cross section with overlaid detected shape pattern, and (3) final export to a finite element in ANSYS. The structural properties extracted by the conversion algorithms are compared to the actual properties as tabulated in AISC 14th ed, as shown in Table 2. Each cross section shape is classified correctly, and the percent error in dimension comparison varies for some beam types. For the W14x730 and MC8x20 beams, cross section dimensions are measured exactly with 0.0% error, but for the

Pipe2-1/2XXS beam, inferred dimensions have a slight error of about 1%. The slight error for the pipe cross section dimensions is because the OBJ geometry is represented by many small triangular polygons, which can only approximate the curvature of circular shapes.

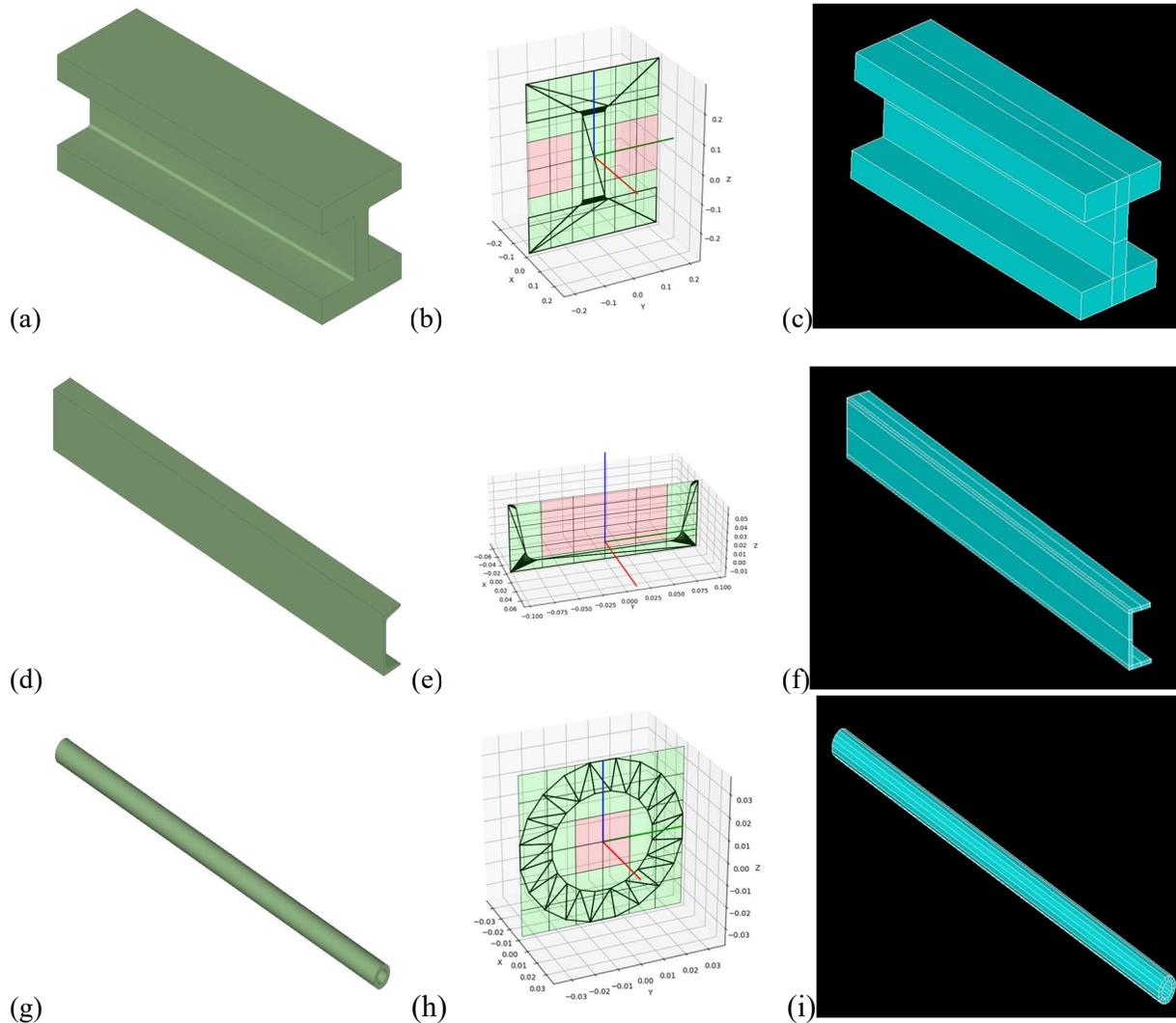


Figure 4. Converted Revit Beams.

1st Row: W14x730 (a) IfcBeam View (b) Local section with shape pattern (c) ANSYS conversion;  
 2nd Row: MC8x20 (d) IfcBeam View (e) Local section with shape pattern (f) ANSYS conversion;  
 3rd Row: Pipe2-1/2XXS (g) IfcBeam View (h) Local section with shape pattern (i) ANSYS conversion

### ***Case study #2 - AVEVA E3D Sample Building***

For the second case study, the conversion algorithms are applied to a multi-story sample building model from AVEVA E3D. The purpose of this case study is to showcase that the geometric location information is accurately captured for the primary structural framing. As shown in Figure 5, the centroidal axes and orientation of the structural framing are properly represented in the finite element model. The performance of the conversion algorithms in both case studies show that frame member elements from different BIM software and of different shapes can be accurately converted from the original BIM model to the finite element domain using geometric inference tools.

Table 2. Comparison of actual and estimated structural properties for Revit beams exported to IFC

AISC Beam Designation	Property Label	Actual Value from Design Table	Estimated Value from Conversion	Error (%)
W14x730	Shape	I Shape	I Shape	Correct
	Depth (in)	22.4	22.4	0.0
	Web Thickness (in.)	3.07	3.07	0.0
	Flange Width (in.)	17.9	17.9	0.0
	Flange Thickness (in.)	4.91	4.91	0.0
MC8x20	Shape	C Shape	C Shape	Correct
	Depth (in)	8.00	8.00	0.0
	Web Thickness (in.)	0.400	0.400	0.0
	Flange Width (in.)	3.03	3.03	0.0
	Flange Thickness (in.)	0.500	0.500	0.0
Pipe2-1/2XXS	Shape	Hollow circular Shape	Hollow circular Shape	Correct
	Outside Diameter (in.)	2.88	2.85	1.04
	Thickness Nom. (in.)	0.552	0.545	1.23

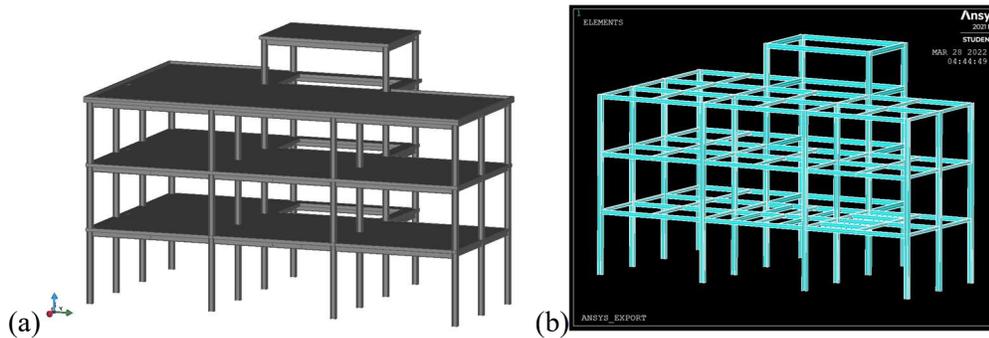


Figure 5. AVEVA E3D Sample Building Model - (a) IFC Representation (b) Converted FE Model

## CONCLUSIONS

Construction costs induced by design changes and communication inefficiency can be reduced by improving the interoperability between BIM and FE analysis tools. However, there is no standardized process for BIM interoperability, and existing methods face technical challenges, particularly for missing information. Therefore, this paper presents two algorithms for the automatic extraction of the geometric location information and structural section information, respectively, of structural framing BIM elements.

The generalized BIM to FE model conversion algorithms aim to be applicable to any structural framing BIM elements that are exported to the IFC file format as IfcBeam, IfcColumn, or IfcMember elements, regardless of the user-defined properties in the IFC file or the type of IFC solid model representation (i.e., frame elements represented by 2D section profiles extruded over a length or more complex frame elements composed of dozens of tessellated polygons). Therefore, IFC data goes through a pre-processing phase whereby the IFC file is converted to the OBJ Wavefront .obj file format using the IfcConvert application. This way, the 3D shape representation of any given BIM frame element can be commonly represented by the tessellated triangular polygons of the OBJ file format. The conversion algorithms utilize the spatial relations of the OBJ geometry data to determine necessary geometric location information for structural modeling, namely the starting and ending cartesian coordinates of centroidal axes. In order to classify the cross section shape, the algorithm first overlays virtual 6x6 grids over the localized cross section of the frame element. The 6x6 grid detects the presence of OBJ polygons in each cell, which is then extruded to a 1D image array and compared against other preset shape patterns based on common AISC beam shapes. After classification of the cross section shape, the algorithm calculates the dimensions by measuring distances from specified reference points.

The conversion algorithm is tested using two case studies: (1) Various AISC steel beams in Autodesk Revit and (2) Sample building in AVEVA E3D. For the Revit case study, the cross section shapes are all classified accurately and the inferred dimensions are calculated to within reasonable percent error of tabulated AISC dimensions. The utility of the geometric location inference algorithm is tested using the AVEVA sample building. The beam and column structural framing of the AVEVA model are all converted accurately and located and oriented appropriately in cartesian space.

### *Limitations and Future Work*

The authors acknowledge two limitations in the application of the conversion algorithms:

1. BIM elements must be straight, prismatic beams without coped ends.
2. Cross section shape classification is limited to the standardized AISC beam shapes. Other custom section types, such as customized built-up I-beams, would not be converted appropriately.

For future work, the algorithms are designed to be scalable so that more cross section shapes can be defined in the presets. Also, the algorithms should be further refined so that they are compatible with more complex and irregular frame member geometry, such as curved frames members or frame members with coped ends and holes.

## REFERENCES

- Adams, R. (2014). Root Cause of Vogtle and VC Summer Delays, Nuclear Newswire. <https://www.ans.org/news/article-1646/root-cause-of-vogtle-and-vc-summer-delays/>
- Aslam M., Baffoe-Twum, E., and Saleem, F. (2019). "Design Changes in Construction Projects – Causes and Impact on the Cost," Civil Engineering Journal, 5(7), 1647-1655.
- Chang A. S. (2002). "Reasons for Cost and Schedule Increase for Engineering Design Projects," Journal of Management in Engineering, 18(1), 29-36.

- Fleming, W. S. 2016. "BIM modelling for structural analysis." Master of Technology: Structural Engineering thesis, Faculty of Civil and Environmental Engineering, Poznan Univ.
- Han S., Love P., and Pena-Mora F. (2013). "A System Dynamics Model for Assessing the Impacts of Design Errors in Construction Projects," *Mathematical and Computer Modeling*, 57(9-10), 2044-2053.
- Ling, Q. I. N., Xue-yuan, D., and Liu, X.-L. "Industry Foundation Classes Based Integration of Architectural Design and Structural Analysis," *J. Shanghai Jiaotong Univ.*, vol. 16, no. 1, pp. 83–90, 2011.
- Muller, M. F., Garbers, A., Esmanioto, F., Huber, N., Loures, E. R., and Canciglieri, O. 2017. "Data interoperability assessment through IFC for BIM in structural design: A five-year gap analysis." *J. Civ. Eng. Manage.* 23 (7): 943–954. <https://doi.org/10.3846/13923730.2017.1341850>.
- Proctor, D. (2021). More Vogtle Delays; Experts Target Mid-2022 Startup at Earliest, News & Technology for the Global Energy Industry. <https://www.powermag.com/more-vogtle-delays-experts-target-mid-2022-startup-at-earliest/>
- Ren, R., Zhang, J., and Dib, H. N. 2018. "BIM interoperability for structural analysis." In Proc., Construction Research Congress 2018: Construction Information Technology, 470–479. Reston, VA: ASCE.
- Thein, V. 2010. IFC Integrating building information modeling. Philadelphia: Bentley Systems.
- Volk, R., Stengel, J., and Schultmann, F. 2014. "Building information modeling (BIM) for existing buildings—Literature review and future needs." *Autom. Constr.* 38 (2014): 109–127. <https://doi.org/10.1016/j.autcon.2013.10.023>.
- Wan, C., Chen, P., Tiong, R. L. K. "ASSESSMENT OF IFCS FOR STRUCTURAL ANALYSIS DOMAIN," *ITcon*, vol. 9, no. June, pp. 75–95, 2004.
- Wang, X., Yang, H., Zhang, Q. "Research of the IFC-based Transformation Methods of Geometry Information for Structural Elements," *J. Intell. Robot. Syst.*, vol. 79, no. 3–4, pp. 465–473, 2015.
- Watson, A. 2011. "Digital buildings—Challenges and opportunities." *Adv.Eng. Inf.* 25 (4): 573–581. <https://doi.org/10.1016/j.aei.2011.07.003>.
- Wu, J., Sadraddin, H. L., Ren, R., Zhang, J. and Shao, X. "Invariant Signatures of Architecture, Engineering, and Construction Objects to Support BIM Interoperability between Architectural Design and Structural Analysis," *J. Constr. Eng. Manage.*, 147(1): 04020148 (2021).
- Yalcinkaya, M., and Singh, V. 2014. "Building information modeling (BIM) for facilities management—Literature review and future needs." In Proc., IFIP Int. Conf. on Product Lifecycle Management. Berlin: Springer.