

Comparison of BIM Interoperability Applications at Different Structural Analysis Stages

Ran REN¹ and Jiansong ZHANG²

¹Automation and Intelligent Construction (AutoIC) Laboratory, School of Construction Management Technology, Purdue University, West Lafayette, IN 47907; e-mail: ren153@purdue.edu

²Automation and Intelligent Construction (AutoIC) Laboratory, School of Construction Management Technology, Purdue University, West Lafayette, IN 47907; e-mail: zhan3062@purdue.edu

ABSTRACT

Building Information Modeling (BIM) provides a novel way of information management for all lifecycle phases of a building project. It is facilitating the processes of a construction project, such as architectural design, structural analysis, and construction management. Industry Foundation Classes (IFC) is an open standard for information exchange between different BIM applications in the Architecture, Engineering, and Construction (AEC) domain. It represents project information in an interoperable way that contains geometric information, material information, and other physical and functional information needed of analyzing and managing a project. Structural analysis aims to simulate the structural performance of a building under different types of loads to make sure the structure is safe. The needed information for structural analysis mainly include geometric, material, and load information. These information come from architectural design and selected analysis scenarios. The information should be represented in an interoperable way to allow information transfer between different phases and different stakeholders. Information missing is a crucial problem during the interoperable use of BIM, which may cause misunderstandings between different stakeholders and therefore erroneous structural analysis result and misleading information to feed construction process later on. In this paper, the authors focus on analyzing the use of IFC at three stages in structural analysis, namely, intrinsic modeling stage, extrinsic modeling stage, and the analysis stage. The authors compared IFC files at these three stages with original BIM software text files in terms of information coverage, and identified information missing cases. This is the first systematic investigation of BIM interoperability at detailed work stages of structural analysis and provides insights in how BIM usage should be improved in this domain.

INTRODUCTION

3D modeling technology has been applied in the construction management domain for many years to improve the visualization and documentation of a construction project (Ma and Liu 2018). Building Information Modeling (BIM) is considered to play a key role in the Architecture, Engineering, and Construction (AEC) domain, which supports the visualization, documentation, and representation of the

geometric, material and functional information in the life cycle phases of a building. Information represented by BIM can be processed and analyzed to support interoperable BIM usage between different applications (e.g., architectural design and structural analysis). Industry Foundation Classes (IFC) is an open and neutral data format for information representation, which is widely used in the AEC domain. IFC-based BIM applications enable the communication and information transfer between different stakeholders (e.g., architects and structural engineers) from one-to-one communication to many-to-one communication, which is a more efficient method of communication and information transfer. IFC-based BIM implementation provides a new approach to support information transfer, processing and analysis for a construction project. Structural analysis relies on simplifications of a structure into simplified elements in a model, such as simplifying beams and columns as straight lines, and simplifying plates as 2D shapes. The structural analysis model is a key element at the structural design stage of a construction project. It is used to simulate the performance of a structure under different types of external load scenarios to test the safety conditions of the building. The steps of conducting structural analysis on the developed structural models integrate the intrinsic information (i.e., geometric information and material information), extrinsic information (i.e., supports information and external load information), and analysis information (i.e., structural analysis results). Information missing in the different structural analysis steps is a critical problem in an interoperable use of BIM, which can affect (1) the efficiency and accuracy of information transfer, processing, and analysis, and (2) the structural analysis results. The information in these three structural analysis stages should be represented in an interoperable way to improve the life cycle use of BIM information to support structural analysis. In this paper, the authors analyzed the information coverage of three different structural analysis stages (i.e., intrinsic, extrinsic, and analysis stages), corresponding to the three types of information, to discuss the information missing problem, and ways to improve the interoperable BIM usage in the AEC domain.

BACKGROUND

BIM has been adopted in many countries since the early 2000s. The BIM implementation helped solve data collection and storage problems and attracted many researchers and organizations to measure its adoption status (van Berlo et al. 2012). BIM technology offers benefits in improved architectural design, structural analysis, safety management, and more efficient scheduling in a construction project, among others. BIM application plays an important role in the structural analysis of construction project. Table 1 shows some existing work using BIM technology for structural analysis applications.

RESEARCH METHDOLOGY

Based on our literature review (Table 1), although the existing work analyzed the BIM applications for structural analysis from different perspectives, they did not

focus on detailed analysis stages of a structural analysis process. To address this gap, the authors analyzed the use of BIM in three different structural analysis stages (intrinsic, extrinsic, and analysis stages) through investigating both the exported text files and corresponding exported IFC files from structural analysis BIM tools to find potential missing information. In this paper, the same structure was created in two structural analysis BIM software – *Software A* and *Software B*, which were used to

Table 1. Existing Work Using BIM for Structural Analysis Applications

Literatures	Main Contribution
Jung and Lee (2015)	A global survey framework was established on BIM adoption status (e.g., structural analysis in the BIM services stage) to show global BIM adoption status.
Jalaei (2015)	A methodology at the conceptual stage was developed to implement sustainable design for planned buildings (e.g., experimental structural analysis in the early design phase).
Dore et al. (2015)	A case study of the Four Courts, a historic classical building in Dublin City was developed using structural simulations and conservation analysis to measure the war damage.
Barazzetti et al. (2015)	The use of Building Information Models (BIMs) for structural simulation based on Finite Element Analysis was discussed. It proved that the interconnections between the different elements of BIMs and their materials required attention to understand the geometric information, i.e., structural elements and their interactions.
Bassier et al. (2016)	A realistic BIM model of a complex roof structure was created, which covered the data acquisition (i.e., employing dense point clouds), the modelling and the structural analysis of this structure.
Jin et al. (2016)	A case study was created to demonstrate the capacity of BIM in assisting the cross-disciplinary project design, including the architectural plan, structural analysis, cost estimate, energy simulation, and their integration.
Liu et al. (2016)	An indirect method was proposed for the data transformation from BIMs to structural analysis models by comparing the differences between BIM physical model and structural mechanical model (e.g., irregular nodes).
Hu et al. (2016)	A new method was proposed which combines IFC-based Unified Information Model with algorithms to improve BIM interoperability between architectural and structural models, and among multiple structural analysis models.
Muller et al. (2017)	The experiments that structural models were imported and exported through IFC standards were conducted, how the use of BIM technology would improve the structural design process was assessed.

Aldegeily et al. (2018)	Three information exchange mechanisms of IFC-based BIMs were analyzed for information transfer from BIM design models to structural analysis models.
Ren et al. (2018)	The interoperable BIM usage in structural analysis among different BIM analysis software was tested and information missing problem among BIMs was found.
Ren and Zhang (2019)	Customized algorithms for checking material information in the structural models were developed to improve BIM interoperability for structural analysis applications in the AEC domain.

export model information into text files and IFC files, respectively. The information coverage in all the three stages for both types of files were analyzed. Figure 1 shows our four-step research methodology. Step 1: Define Structural Analysis Stages - This step defines three structural analysis stages in which BIM information coverage will be studied. Step 2: Analyze Exported Text Files of Different Analysis Stages – This step analyzes three different structural analysis stages in their exported text files from a structural analysis BIM software, which construes a horizontal discussion of information coverage (i.e., compares and analyzes information coverage in the same type of file at three different stages). Step 3: Analyze Exported IFC Files of Different Analysis Stages – This step analyzes three different structural analysis stages in their exported IFC files from a different structural analysis BIM software comparing to Step 2, which is also a horizontal discussion similar to Step 2. Step 4: Compare Exported Text Files and IFC Files in Information Coverage – This step comparatively analyzes information coverage between text files and corresponding IFC files which are converted from proprietary BIMs, which construes a vertical discussion of information coverage (i.e., compares and analyzes information coverage between different types of files).

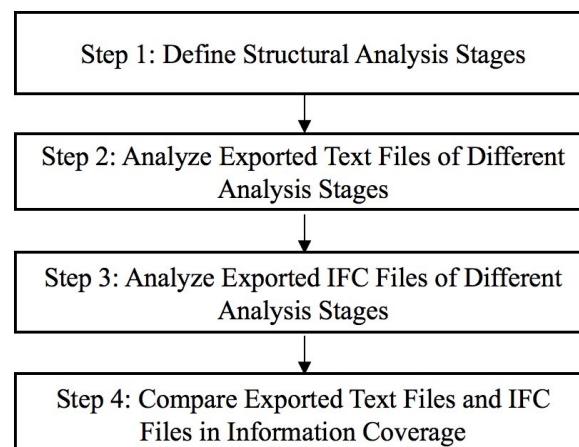


Figure 1. Research methodology

Step 1: Define structural analysis stages

Structural analysis integrates a set of mechanics theories that follow the physical laws to predict the behavior of a structure under different types of analysis scenarios (Kuang-HuaChang 2015). A typical structural analysis process runs as follows: (1) create geometric information and assign material information to each element; (2) set supports information and define load information; (3) run structural analysis and report the result. In this paper, the authors proposed the division of the structural analysis process into three stages: intrinsic stage, extrinsic stage and analysis stage (Figure 2). At the three different structural analysis stages, geometric and material information, supports and load information, and structural analysis results are represented, respectively.

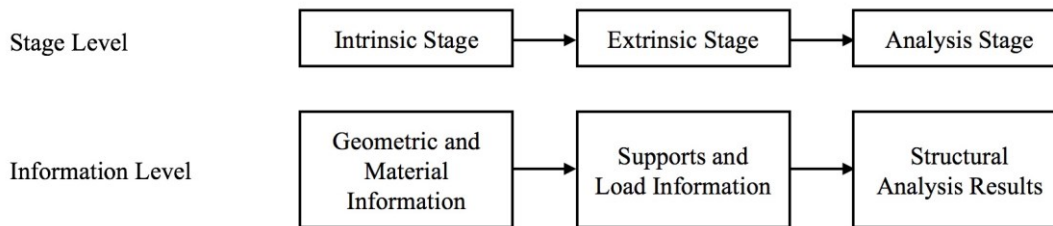


Figure 2. Three structural analysis stages

Step 2: Analyze Exported Text Files of Different Analysis Stages

In this paper, a simple structure was used, which contained four beams and four columns (Figure 3) to analyze the information in the different text files at the three stages: (1) a text file of BIM model with geometric and material information only, (2) a text file of BIM model with supports and load information added, and (3) a text file of BIM model with structural analysis results further added (Figure 4). However, the structural analysis results could not be exported from *Software A* [Figure 4(c)], which shows the information missing problem when exported text files from *Software A* at the analysis stage. Only the geometric, material [highlighted in the Figure 4(a)], supports [highlighted in the Figure 4(b)] and load information [highlighted in the Figure 4 (b) (c)] could be exported to text files from *Software A*.

Step 3: Analyze Exported IFC Files of Different Analysis Stages

IFC-based BIMs enable the information integration and representation of the different application models to support BIM interoperability. In this step, the same BIM model was created in *Software B* which had been created in *Software A* in Step 2, to analyze information coverage in the three structural analysis stages. Figure 5 shows the partial IFC file exported from *Software B* at the extrinsic stage. In the IFC file, the geometric and material information can be mainly defined by “*IfcCartesianPoint*” and “*IfcMaterial*” entity instances, respectively (Figure 5). Load information can be represented by “*IfcRelAssignsToGroup*” entity instance to assign load information to

different elements in the structure (Figure 5). After comparing the IFC files at the three stages, only the geometric, material, supports and load information could be exported to IFC files from *Software B*. Structural analysis results could not be exported to IFC file based on the IFC data analysis. There is an information missing problem when exporting the IFC file from *Software B* at the analysis stage.

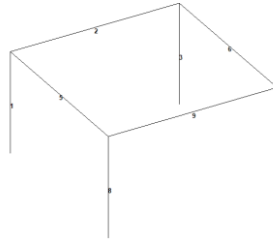
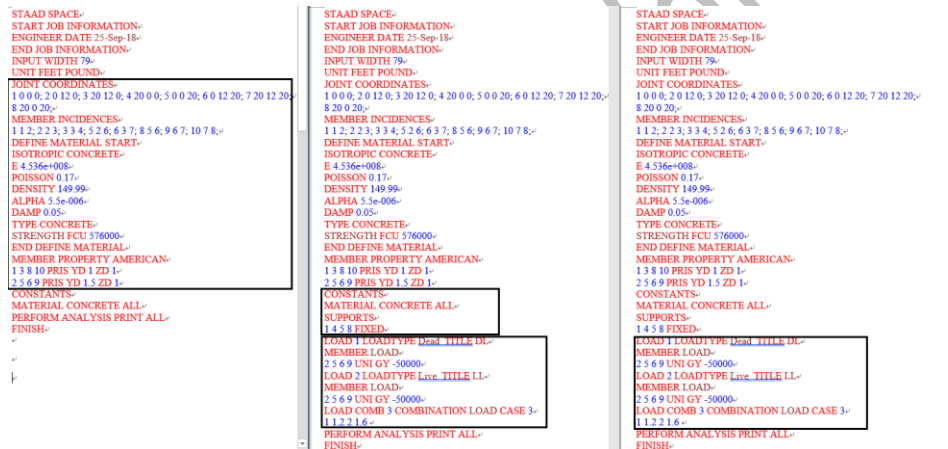


Figure 3. A simple beam-column structure in *Software A*



(a) Intrinsic Stage

(b) Extrinsic Stage

(c) Analysis Stage

Figure 4. Text files exports of *Software A* at three stages

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#28=IFCDERIVEDUNIT((#59,#60),.PLANARFORCEUNIT.,$);
#29=IFCDERIVEDUNIT((#61,#62,#63),.LINEARMOMENTUNIT.,$);
#30=IFCDERIVEDUNIT((#64,#65),.SHEARMODULUSUNIT.,$);
#31=IFCDERIVEDUNIT((#66,#67),.MODULUSOFELASTICITYUNIT.,$);
#32=IFCCONVERSIONBASEDUNIT((#68,.THERMODYNAMICTEMPERATUREUNIT.,'FAHRENHEIT',#69);
#33=IFCDERIVEDUNIT((#70),.THERMALEXPANSIONCOEFFICIENTUNIT.,$);
#34=IFCFACTORROLE(.STRUCTURALENGINEER.,$,);
#35=IFCFACTORROLE(.MANUFACTURER.,$,);
#36=IFCCARTESIANPOINT((0.00000000E+000,0.00000000E+000,0.00000000E+000));
#145=IFCMATERIAL('4000Psi');
#146=IFCPROPERTYSINGLEVALUE('CompressiveStrength',$,IFCPRESSUREMEASURE(5.7600000E+005),#26);
#147=IFCPROPERTYSINGLEVALUE('MassDensity',$,IFCMASSDENSITYMEASURE(4.6621422E-003),#23);
#148=IFCPROPERTYSINGLEVALUE('PoissonRatio',$,IFCRATIOMEASURE(2.0000000E-001),$);
#149=IFCPROPERTYSINGLEVALUE('ShearModulus',$,IFCSHEARMODULUSMEASURE(2.1629979E+003),#30);
#150=IFCPROPERTYSINGLEVALUE('ThermalExpansionCoefficient',$,IFCTHERMALEXPANSIONCOEFFICIENTMEASURE(5.5000000E-006),#33);
#151=IFCPROPERTYSINGLEVALUE('YoungModulus',$,IFCMODULUSOFELASTICITYMEASURE(5.1911950E+005),#31);
#239=IFCRELATIONSHIPGROUP('2tkthN51E6Q1jvYPeKSh',#3,$,($4,$101,$106,$111,$116,$121,$126,$131,$136,$157,$165,$173,$181,$197,$211,$225),.PRODUCT.,#52);
#240=IFCRELATIONSHIPGROUP('1E6U4PWEUA50ZUSUIMP',#3,$,($191,$205,$219,$233),.PRODUCT.,#85);
#241=IFCRELATIONSHIPGROUP('1C18A 1B6DFC1UotmarVM',#3,$,($192,$206,$220,$234),.PRODUCT.,#87);
```

Figure 5. An example partial IFC file exported from *Software B*

Step 4: Compare Exported Text Files and IFC Files in Information Coverage

The authors compared information transfer by exported text files and IFC files from different BIM analysis software of the same BIM model from the horizontal

comparison perspective in *Step 2* and *Step 3*, respectively. In the current step, the authors compared the information coverage between text files and corresponding IFC files from the vertical comparison perspective and found that: (1) the text file was more concise than the corresponding IFC file of the same model. For instance, in the text file, material property definitions were represented straightforwardly in the highlighted content in Figure 4(a), e.g., E and POISSON represented Young's Modulus and Poisson Ratio of material properties, respectively. In the IFC file, material properties were represented by "IfcPropertySingleValue" entity instance. The property name and numerical information were defined by the "Name" and "NominalValue" attributes of an "IfcPropertySingleValue" entity instance, e.g., IFCPROPERTYSINGLEVALUE('PoissonRatio', \$, IFCRATIOMEASURE(2.0000000E-001), \$). The "Name" attribute was defined by the string "PoissonRatio". The "NominalValue" attribute was represented by "IFCRATIOMEASURE(2.0000000E-001)" (Figure 5). (2) The function of importing and exporting text files was not available in every BIM analysis software. The text files exported from different BIM analysis software were different. Different BIM analysis software can only read specific text files generated by themselves. It is a software-depended and text-file-function-depended method to transfer data. (3) The IFC file contains more reference information than the corresponding text file. For example, the IFC file has its own format structure to define Unit information in the model (Figure 6). The unit is consisted of two parts - the representation of unit format is A*B, e.g., the unit of mass density will be represented by (kilogram ^ 1) * (millimeter ^ -3). In contrast, the text file export did not contain unit information of material, only numerical information was found.

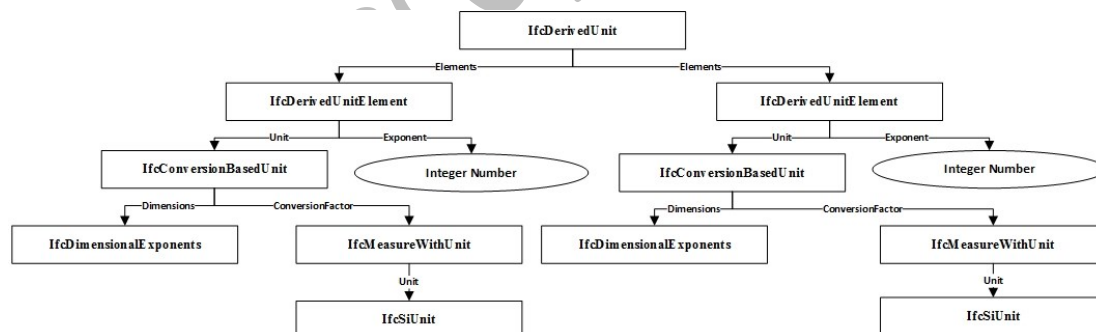


Figure 6. IFC format structure of defining unit information in the model

STAGES ANALYSIS RESULTS AND AN STAGE-INFORMATION-FILE SYSTEM

Information coverage analysis results are shown in Table 2. Only structural analysis results could not be exported to the test file from *Software A* and IFC file from *Software B*. Geometric, material, supports, and load information could be exported both to the text and IFC files. Intrinsic stage was the first step to conduct structural analysis. At the intrinsic stage, geometric and material information were added to the model as

the input. All the information elements (i.e., geometric and material information elements) could be exported from *Software A & B*. Extrinsic stage was the second step to conduct structural analysis. At the extrinsic stage, supports and load information were added on top of the model at the intrinsic stage. All the information elements (i.e., geometric, material, supports, and load information elements) could be exported from *Software A & B*. Analysis stage was the third step to conduct structural analysis, at the analysis stage, structural analysis was conducted in the BIM analysis software based on the model at the extrinsic stage. Structural analysis results would be represented by Von Mises stress, axial force, and torsion structural analysis results. However, the structural analysis results could not be exported from BIM analysis software neither to the text file nor to the IFC file.

To explain the information coverage among the three structural analysis stages, the authors proposed a new stage, information, and file (SIF) system model (Figure 7). The system model includes three different implementation levels: stage level, information level, and file level. The stage level provides structural analysis stages, which are intrinsic, extrinsic, and analysis stages. Each stage contains different types of structural analysis information, i.e., intrinsic stage contains intrinsic property information of a structure, extrinsic stage contains extrinsic information to be added during the structural analysis, and analysis stage further adds analysis results. Information level indicates the required information in the BIMs for structural analysis, they are geometric and material information, supports and load information, and structural analysis results information. Different types of information are required in different structural analysis stages, e.g., geometric and material information is required in all three analysis stages, supports and load information is required at the extrinsic and analysis stages. All types of information except structural analysis results information need to be manually input or transferred from other models when structural analysis is performed. The file level contains text, IFC, and other types of files of the BIM information between which information coverage analysis can be studied. The stage level defines required information for the information level, and the information level instantiates the definitions of different stages. Information level analysis is based on the different types of files at the file level, and the different files at the file level carry the required information at the information level. The three levels are interconnected in the system.

Table 2. Information Coverage Analysis

Information Coverage	Geometric and Material Information	Geometric, Material, Supports and Load Information	Geometric, Material, Supports, Load Information and Structural Analysis Results
Stages	Intrinsic Stage	Extrinsic Stage	Analysis Stage
Text File	✓	✓	Missing Structural Analysis Results

IFC File	✓	✓	Missing Structural Analysis Results
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The stages analysis system is consisted of three levels, which contains the main paths of information transfer during a structural analysis process. The solid arrows represent solid connections between two levels, the dashed arrows represent questionable connections. For example, the dashed arrows between information level and file level show that structural analysis results currently cannot be exported neither to the text file nor to the IFC file from BIM analysis software. Each stages analysis path will be consisted of three blocks from the three different levels that are connected through two arrows. The analysis of information coverage among other types of files is out of the scope of this paper.

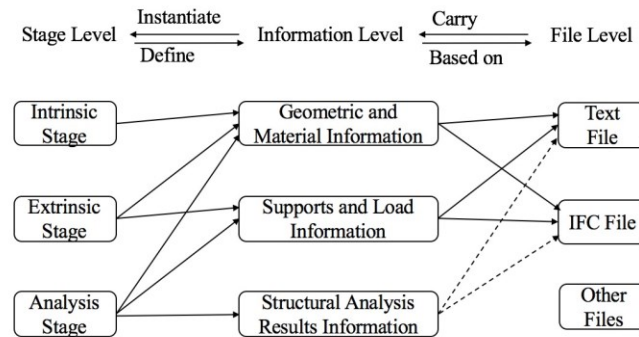


Figure 7. Stage-information-file (SIF) system

CONCLUSION

Information missing during model exportation from BIM structural analysis software is an important problem that needs to be solved to support BIM interoperability in the AEC domain. To address this problem, the authors conducted a preliminary analysis of the information coverage among three structural analysis stages (i.e., intrinsic, extrinsic, and analysis stages) from text and IFC files exported from different structural analysis BIM software. The files exported from the same BIM model were compared in horizontal and vertical perspectives. The results showed that (1) models could be exported as text files and IFC files from BIM analysis software, (2) geometric, material, supports and load information could be exported both to the text files and IFC files from BIM analysis software, and (3) structural analysis results could not be exported from BIM analysis software directly neither to text nor to IFC files. With the anticipated full life cycle comprehensive information support goal of BIM for structural analysis, more research and development need to be done to close the roundtrip information transfer loop for all intrinsic, extrinsic, and analysis results information.

LIMITATIONS AND FUTURE WORK

Two main limitations of this paper are acknowledged: (1) only text files and IFC files were covered. In future work, the authors plan to investigate the information coverage in other types of files such as XML file; (2) only a simple structural model was used to analyze the information coverage in three different analysis stages. In future work, the authors plan to analyze the information coverage in more complex models with more types of information. The discussion can be useful to support development of interoperable BIM platform, which could further embed other information such as as-built information by developing new data representation structure for physical and functional data collected with sensors.

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