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The Building Information Modeling and its Use for Data Transformation in the Structural Design Stage

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Abstract

As a processing technology of data and information, building information modeling (BIM) is often used for producing digital engineering model and promoting interoperability among participants involved in the Architecture, Engineering, and Construction (AEC) industry. The real values of BIM largely depend on effective information integrating and sharing among different stages or disciplines through the whole building lifecycle. To this day, although BIM has made a substantial contribution to the Chinese AEC industry, there are still some debates on its roles. Moreover, due to the complexity of structural design process, the weak link between structural model and BIM model makes its deep application even harder. To address these issues, this paper discusses the roles of BIM from the perspective of structural engineers through comparing with the traditional CAD. Then, the BIM structural model is studied by analyzing the model conformation, design mode, and Industry Foundation Classes (IFC)-format structural model. By comparing the differences between BIM physical model and structural mechanical model, an indirect method for the data transformation from BIM model to structural analysis model is proposed. An interface is developed based on the analysis of data formats and mapping rules. Three typical cases are adopted to demonstrate the data transfer efficiency by using the interface. The case study shows that the proposed method achieves higher efficiency for the data transformation from BIM model to structural analysis model.

Key Words: BIM Technology, IFC-format BIM Model, Structural Analysis Model, Data Transformation Interface, Information Integrating and Sharing

1. Introduction

With the development of building information modeling (BIM) in the Architecture, Engineering, and Construction (AEC) industry, an increasing number of building participants are now paying close attention to this technology on their projects. For some, BIM is regarded as a software application; for others, it is a process used for designing and managing building information. The definitions and characteristics of BIM have been introduced in many articles. Most articles attempt to define BIM in their own terms and, with over hundreds articles on this topic, BIM often takes on a variety of definitions [1–5]. In the American National BIM Standard (NBIMS), a definition of BIM is as follows: "BIM is defined as a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward [6]."

The report of McGraw Hill thinks that BIM is being deployed on a growing variety of project types all over

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the world, not only in buildings but infrastructure, industrial and natural resources projects as well [7]. In the AEC industry, building design, construction management, and building energy analysis are three mature application stages of BIM. Although BIM is regarded as another revolution following the CAD technology, for its deep application, there is still a long way to go. For example, when the roles of BIM are concerned, different structural engineers may hold different opinions in the Chinese AEC industry. Furthermore, the information integrating and sharing in some stages of a building is still difficult to implement. These issues, to some extent, hinder the sustainable development of BIM [8–12].

The building design process, which mainly includes architectural design, structural design and MEP (mechanical, electrical and plumbing) design, often produces mass data and information. In general, the structural design and MEP design depend on the effective sharing of data and information produced from the architectural design. The structural design is a complex and dynamic process, in which the structural mechanical behavior under the effect of different loads needs to be calculated and analyzed. A structural model is an essential component of BIM model, and plays a vital role in the building design process [13,14]. Therefore, some BIM-based studies in the structural design stage are on the rise in recent years.

Chi, H. L. et al. discussed the impacts and potential development trends of BIM-enabled structural design through a comprehensive survey regarding the structural design practice and current status of BIM adoptions [15]. Nawari, N. O. and Sgambelluri, M. investigated the general objectives of the NBIMS and its relationship to structural engineering practice through focusing on the importance of involvement and contribution of structural engineering community to this standard [16]. To obtain more optimized design solutions and reduce the waste caused by the repetitive work that frequently occurred in point-based design (PBD) procedure, Lee, S. I. et al. improved the set-based design (SBD) procedure for increasing the analysis efficiency of high-rise building structure based on the structural building information modeling [17]. To handle the data exchange between IFC-compatible architectural models and structural models, Qin, L. et al. proposed a central building information modeling framework based on the IFC [18]. To assist construction managers or owners to analyze and manage the process conflict and structural safety problems during engineering construction, Zhang, J. P. and Hu, Z. Z. proposed a new approach for conflict and safety analysis during construction through integrating construction simulation and 4D construction technology [19]. To show the impact of BIM on structural engineers, Lancaster, F. D. and Tobin, J. outlined the extensive experiences of an engineer and an architect with BIM in all design disciplines, as well as their ongoing efforts in working with contractors on BIM models [20]. To show the migration from 2D to 3D solutions, Robinson, C. discussed the application status of building information modeling (BIM) from the structural point of view, and identified the benefits obtained from the structural BIM solution through two case studies [21].

Although there is still no efficient method to exchange data and information successfully from the structural design stage and the weak link still exists between structural model and BIM model, the above studies play a key role in realizing the intercommunication of data and information during the entire building design process. What is more, these studies contribute to the further application of BIM to the structural design stage.

The first aim of this research is to discuss the roles of BIM from the perspective of structural engineers. Then, the BIM structural model is studied and an indirect method for the data transformation from IFC-format BIM model to structural analysis model is proposed by comparing the differences between BIM physical model and structural mechanical model.

The remainder part of this paper is organized as follows: in section 2, the roles of BIM are discussed from four aspects through comparing with the traditional CAD. Section 3 introduces the BIM structural model through analyzing the model conformation, design mode, and IFC-format structural model. Section 4 focuses on studying the data transformation method and data mapping rules through analyzing the differences between BIM physical model and structural mechanical model; based on Revit (a BIM tool) and YJK (a Chinese structural design software), an interface for indirect data transformation is developed. In section 5, three cases are adopted to demonstrate the data transfer efficiency from IFC-format BIM model to structural analysis model by using the interface, and the application results are also analyzed. Discussion and conclusion are given in the last section.

2. BIM Roles

Currently, there are different opinions about how to understand and use BIM in the Chinese AEC industry. Some structural engineers think that BIM is similar to CAD and can be realized through several types of software applications, others argue that BIM can not be truly realized in the future due to the too wide application scope [22,23]. These different opinions, to some extent, may mislead structural engineers as BIM and its support tools are further applied to the AEC industry.

BIM is, in fact, a logical successor to the traditional CAD. A 3D entity (digital) model allows powerful coordination with 2D drawings, clash detection, and cost estimating. With BIM one can create a virtual building model for architecture members, not just lines. Due to adopting a parametric modeling technology, BIM model has a relevant modification function. This is an essential difference between BIM and traditional CAD.

Compared with the traditional CAD, the roles of BIM can be explained from four aspects. Firstly, BIM is often regarded as a multi-dimensional data model. There are different methods to represent a building data model. For example, BIM can use 3D model to represent the geometrical information of a building, or can adopt 4D model that combines time dimension with 3D model to achieve virtual construction and collision analysis, or can choose 5D model that combines cost dimension with 4D model to analyze the cost of a building, or even can use 6D, 7D, until nD model to manage the data and information across the whole building lifecycle. Although using traditional CAD can also create a 3D model, a superficial 3D model can not be regarded as a BIM entity model.

Then, BIM platform provides an opportunity for cooperative work. For example, the cooperative work among different stages or disciplines can be achieved by using open standard such as IFC. The data model of design stage can be quickly transmitted at any time or any place to the downstream construction stage for effective cooperation. Similarly, the data model of construction stage can be seamlessly transmitted to the operation stage for dynamic building maintenance and management. Through full interoperability, the work efficiency and building quality are improved, along with fewer costs and resources. On the contrary, using traditional CAD can only create respective models for different stages or disciplines, and the relationships among various models can only be linked by hand.

Thirdly, BIM tools contribute to the information integration because lots of software applications or technologies are adopted. In the AEC industry, due to the mass amounts of engineering data and the dispersive processes among different stages or disciplines, it is difficult to realize the lean management for building construction. The proper use of BIM can allow relevant disciplines to obtain required data and information quickly and furthermore, BIM sub-models created by different stages can finally be unified for realizing information exchanging and sharing, which greatly reduces the low efficiency resulted from poor information communication and repetitive work.

Finally, BIM offers an environment for the purpose of virtual construction and visual analysis. The powerful functions of visual display and analysis can help designers discover the potential problems such as code incongruity, design mistake, and construction collision during the building construction process. The BIM-based 3D entity model can be adopted for optimizing the design quality and reducing some possible errors during the design stage. Furthermore, the proper use of 4D virtual technology can improve the construction quality and promote the ability of intuitive communication with building owners.

3. BIM Structural Model

3.1 Conformation and Design Mode

The successful use of BIM, to some degree, depends on whether or not the information produced by different stages or disciplines can be exchanged or shared successfully through the whole building lifecycle. For example, in the building design stage, the assessment criterion is determined by the effective information integration between architectural model and structural model. On the basis of BIM, the data transfer among structural model, architectural model, and construction model is showed in Figure 1 [21].

The BIM structural model is divided into analysis model and detailed model (see Figure 1). The detailed model mainly includes the structural geometrical shapes, section properties, and materials extracted from architectural model. The analysis model often contains plenty of geometrical information such as axis position, mem-

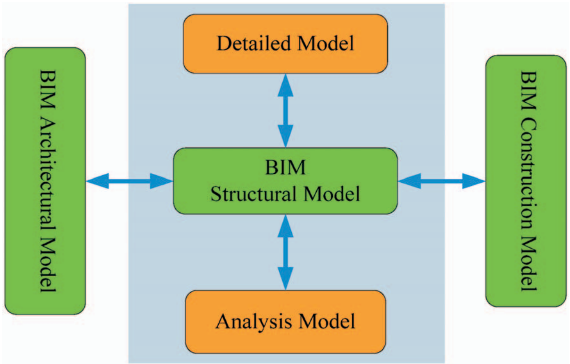

Figure 1. Data transfer among different BIM models.

ber size, and space layout and division, which also are extracted from architectural model. Other information needs to be created by structural engineers including mechanical property, connection type, boundary condition, loading information, etc.

In the traditional structural design, structural analysis and construction drawing usually are two independent stages. The structural analysis is used for assisting construction drawing and confirming the final size and reinforcement of structural members. If BIM is adopted, the two stages can be integrated. Thus, the real-time data can be shared through BIM structural model, which further reduces errors, losses, and code discordance in the construction drawing stage (see Figure 2). In addition, BIM structural model contributes to analyzing and checking the results produced in the structural analysis stage for reducing repetitive work and improving design efficiency and quality [21].

The advantages of adopting BIM during the structural design process are as follows: (1) in the schematic design stage, any modified information operated by structural engineers can be immediately captured by upstream architects. (2) It enables structural engineers to achieve cooperative work with other participants throughout the whole design team. (3) The final data and information produced in the structural design stage can be seamlessly transmitted and shared among different disciplines.

3.2 IFC-Format Structural Model

The BIM model is represented by IFC standard. IFC provides the data definition rule and exchange format for BIM, in which the data is represented by EXPRESS language and EXPRESS-G chart. IFC is an open standard for data representation and enables participants involved to share and exchange data and information produced by different stages. Currently, the latest version is IFC4 Add1, which was released by BuildingSMART as the final standard in July 2015 [24]. Since the first version was released in 1996, IFC has been generally accepted by more and more building software applications, especially some international building software companies. In addition to architectural design, products of these software companies have also supported IFC in the following parts including structural design, MEP design, and steel detailed design. However, the degree of supporting in the environment analysis, cost evaluation, and facility management is still in the infant stage. The definition of IFC model is very complex. The data format and model hierarchy are extremely complicated, even for the definition of one simple building member. For example, in IFC4 Add1, it includes about 392 data types, 768 entities, and 634 property sets, among which there also have complex constraint rules and relationships such as mutual cross connection, reference, inheritance, etc.

In the hierarchical division of IFC model, the structural model is mainly comprised of two parts, namely, structural elements domain and structural analysis domain. Combining with the object-oriented semantic definition mode of IFC, the development of BIM structural model was listed in the Applied Technology Council project (ATC)-75 by NBIMS and linked with IFC [25]. The elements domain mainly represents various structural members or member assembles. The analysis domain mainly covers 2D plane model and 3D spatial model, such as geometrical definitions of point, line, and plane, as well as loading mode, boundary condition, and analysis result.

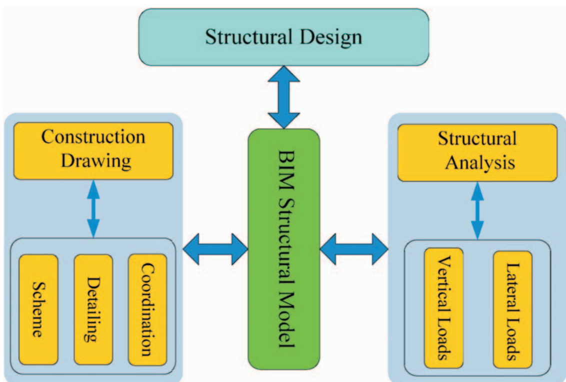

Figure 2. BIM-based structural design mode.

4. Data Transformation Methodology

4.1 Analysis Software Applications

About more than 150 types of software applications have been certified by BuildingSMART to support output and input of IFC-format data. Some big software applications, such as Revit, ArchiCAD, and Bentley, are widely applied to the building design process including architecture, structure, and facility [24].

In the AEC industry, the analysis software applications mainly include ETABS, MIDAS, ABAQUS, ANSYS, and SAP2000. Enormous solution scale and effective non-linear analysis are the two obvious functions of these analysis software applications. However, due to the deficiency of concepts of structural engineering, some undesired results are often received when these analysis software applications are used for structural modeling, especially for the complex building structures. As a result, structural engineers have no enough time to consider detailed modeling in the structural analysis process, which further results in the poor quality of structural design. On the contrary, if the numerical modeling of these analysis software applications is efficient and accurate, it not only provides a reliable reference for the structural design specification, but also helps structural engineers evaluate the structural response behavior and failure mechanism effectively. Therefore, when combining with BIM, a link must be established with these analysis software applications. A variety of analysis software applications can make the best of the function of data integrating and sharing of BIM when "information isolated island" is solved in the structural design stage. Currently, although some analysis software applications, such as ETABS and SAP2000, claim that they have been supported by BIM, the degree of supporting is extremely low, and can not realize the data transformation of structural model successfully. Meanwhile, the formats of data modeling of many analysis software applications are mutual independence, and also don't allow the input and output of IFC-format data.

4.2 Adopted Method

In general, an architectural scheme is often represented by different structural schemes with flexible patterns of bearing capacity in the structural design stage, which results in the complexity of structural modeling. Moreover, the representation between structural mechanical model and BIM physical model is greatly different. It is difficult to develop a direct link with IFC-format BIM because some connected nodes of members need to be modified to achieve data transformation between the two models.

For example, a BIM 3D physical model contains an irregular connected node between an inclined beam and an unequal-high column (see Figure 3(a)), as well as a relevant structural mechanical model (see Figure 3(b)). In the mechanical model, the difference can not be shown between this irregular node and other node, and must be modified by hand. This issue is only a simple example produced by a simple framework. In fact, even if a simple building usually contains tens of thousands connected nodes. Since lots of modifications are required, it is not practical for structural engineers to develop a direct link between IFC-format BIM and analysis software applications.

Combining with IFC-format BIM model, an indirect method for data transformation is adopted in this research (see Figure 4). In the first step, a BIM tool (Revit) is adopted to create IFC-format model, and next, the model is extracted by a Revit interface to a structural design tool (YJK). Then, the BIM structural model is extracted again from the structural design tool (YJK) to some analysis software applications.

4.3 Data Transfer Interface

Figure 4 shows the workflow of indirect method for

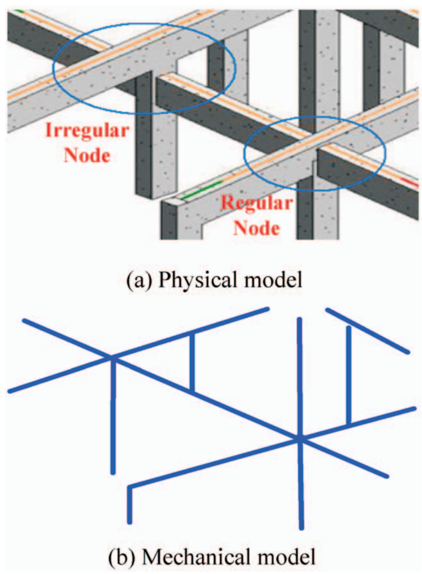

Figure 3. Difference between two models.

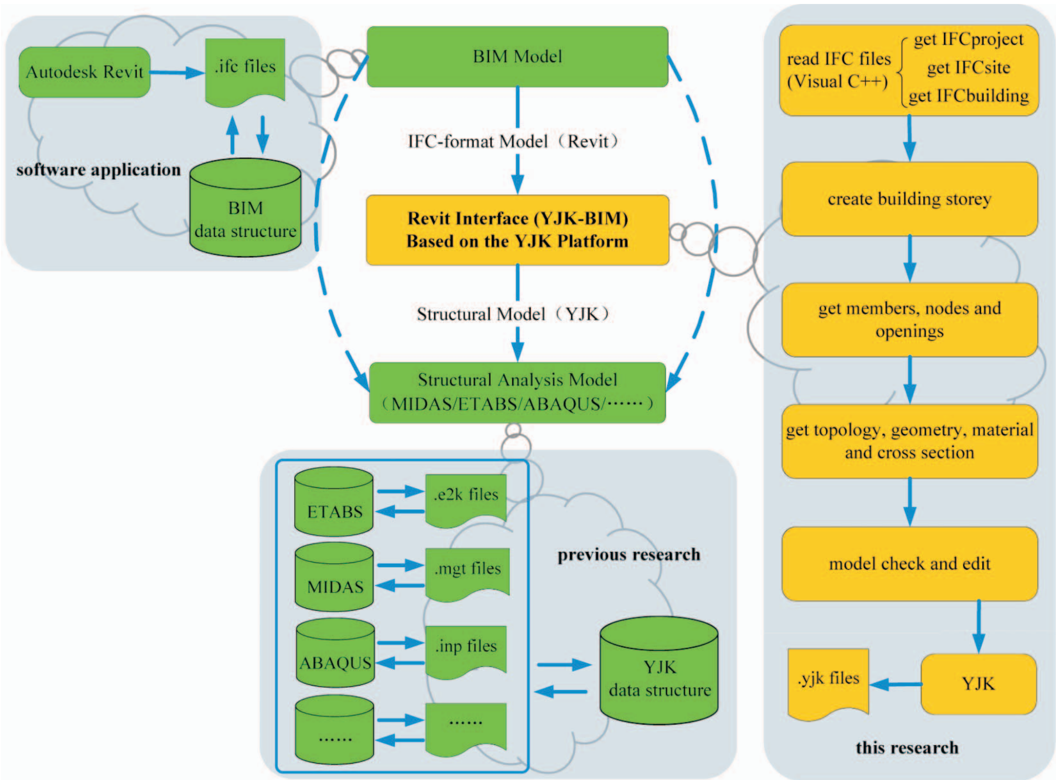

Figure 4. Workflow of data transformation.

data transformation between BIM model and structural analysis model (indicated by dotted arrow), in which the solid arrow represents direct data exchange through the central Revit interface. In the research, the Revit interface is developed based on the YJK platform. Because the current IFC4 Add1 version has covered general types of cross sections of structural members that used by YJK, the technical difficulty of data transformation is greatly reduced between two different format models. Since the structural model produced by YJK has achieved data transfer with some analysis software applications (such as MIDAS, ETABS, SAP2000, and ABAQUS), the development of Revit interface is focused on the data transfer from IFC-format BIM model to YJK structural model.

Based on the IFC-format files and YJK, the Revit interface is developed by using plug-in components into YJK platform, and C++ language is adopted to develop an integrated framework of interfaces.

Figure 5 shows the integrated framework of interfaces. There are lots of control toolboxes developed for the data transformation between YJK and other models in the framework. The far left toolbox is Revit interface (YJK-BIM), others that have been developed in previous studies, are PKPM interface, MIDAS interface, ETABS interface, SAP2000 interface, ABAQUS interface, etc.

4.4 Data Mapping Rules

The file types of EXPRESS in IFC mainly include schemata, data types, entities, algorithms, rules, etc., in which the data types are comprised of simple type, defined type, composite type, aggregate type, and entity type. Since the entity type also includes other data types, the data mapping between EXPRESS and C++ is mainly focused on the mapping of entity type. Normally, an entity type is mapped into a class in C++, and the entity attributes and rule constraints of EXPRESS are mapped into member variables and member functions in C++ respectively. The relationships among entities are represented by the relationships among classes, and the relationships of “reference” and “inheritance” among entities are mapped into inheritance relationships of classes. The entities represented by C++ must keep corresponding relationships one by one with their structures in EXPRESS. Taking the “IfcStructuralLoadSingleForce” entity as an example, the specific EXPRESS descriptions

Figure 5. Integrated framework of interfaces.

and corresponding mapping codes of C++ are shown as follows.

(1) EXPRESS
ENTITY IfcStructuralLoadSingleForce
SUPERTYPE OF (IfcStructuralLoadSingleForceWarping)
SUBTYPE OF (IfcStructuralLoadStatic);
    ForceX: **OPTIONAL** IfcForceMeasure;
    ForceY: **OPTIONAL** IfcForceMeasure;
    ForceZ: **OPTIONAL** IfcForceMeasure;
    MomentX: **OPTIONAL** IfcTorqueMeasure;
    MomentY: **OPTIONAL** IfcTorqueMeasure;
    MomentZ: **OPTIONAL** IfcTorqueMeasure;
END_ENTITY;

(2) C++
```
void Add_IFCSTRUCTURALLOADSINGLEFORCE
(long _enID, long & iNo)
{
    IFCSTRUCTURALLOADSINGLEFORCE.nID
=_enID;
Get_Name(IFCSTRUCTURALLOADSINGLEFORCE.
name);
IFCSTRUCTURALLOADSINGLEFORCE.fX=Get_
value1();
IFCSTRUCTURALLOADSINGLEFORCE.fY=Get_
value1();
IFCSTRUCTURALLOADSINGLEFORCE.fZ=Get_
value1();
IFCSTRUCTURALLOADSINGLEFORCE.mX=Get_
value1();
IFCSTRUCTURALLOADSINGLEFORCE.mY=Get_
value1();
IFCSTRUCTURALLOADSINGLEFORCE.mZ=Get_
value1();
iNo=gIFCSTRUCTURALLOADSINGLEFORCE.size
();
gIFCSTRUCTURALLOADSINGLEFORCE.insert
(gIFCSTRUCTURALLOADSINGLEFORCE.end(),
IFCSTRUCTURALLOADSINGLEFORCE);
    nextToken();
}
```

The IFC-format files produced by Revit often contain much repeat information. In order to reduce redundant data and improve data transfer efficiency, each letter of an IFC entity is classified according to its ASCII code when it is read in by the main program of Revit interface. For instance, an "IFCSIUNIT" entity is often regarded as a unit of measurement of members in Revit. In this case, every letter is coded according to its digital sequence. The default values of front three letters "I, F, and C" correspond to 0, 1, and 2, respectively. Then, other letters, such as S, I, U, N, I, and T, are equal to 3, 4, 5, 6, 7, and 8, respectively. The relevant digits and ASCII codes of corresponding letters are multiplied and then added. In this case, "IFCSIUNIT" is equal to value of $3 \times 83 + 4 \times 73 + 5 \times 85 + 6 \times 78 + 7 \times 73 + 8 \times 84$, which is 2617. Thus, the numerical value of 2617 is used for representing "IFCSIUNIT" exclusively.

5. Case Study and Results Analysis

5.1 Case Study

In this section, on the basis of YJK platform, three analysis software applications including MIDAS, ETABS, and ABAQUS, are adopted to demonstrate the application of Revit interface for data transformation through using the integrated framework.

MIDAS, a common analysis software application in the AEC industry, is often used for calculating and analyzing the spatial structures with large-span or complex constraint relations (such as stadium, station, etc.). Firstly, the IFC-format BIM model produced by Revit is transferred into YJK platform by using Revit interface. Then, the extracted structural model is transferred into MIDAS by using MIDAS interface to realize data transformation from BIM (see Figure 6).

ETABS, an integrated analysis software application, can be applied to various structural systems including frame system, braced frame system, shear wall system, and multi-tower system. As before, through the use of Revit interface and ETABS interface, the IFC-format BIM model produced by Revit and the corresponding structural analysis model of ETABS are shown in Figure 7.

As a common analysis software application, ABAQUS focuses on solving structural stress and displacement, structural vibration and acoustic analysis, and rock and soil mechanical analysis. Furthermore, ABAQUS has an abundant element library that can simulate any geometrical shapes of structural elements as well as various kinds of material model library for simulating the performances of typical building materials. Similarly, through the use of Revit interface and ABAQUS interface, the IFC-format BIM model produced by Revit and the corresponding structural analysis model of ABAQUS are shown in Figure 8.

5.2 Results Analysis

The case study adopts three different types of struc-

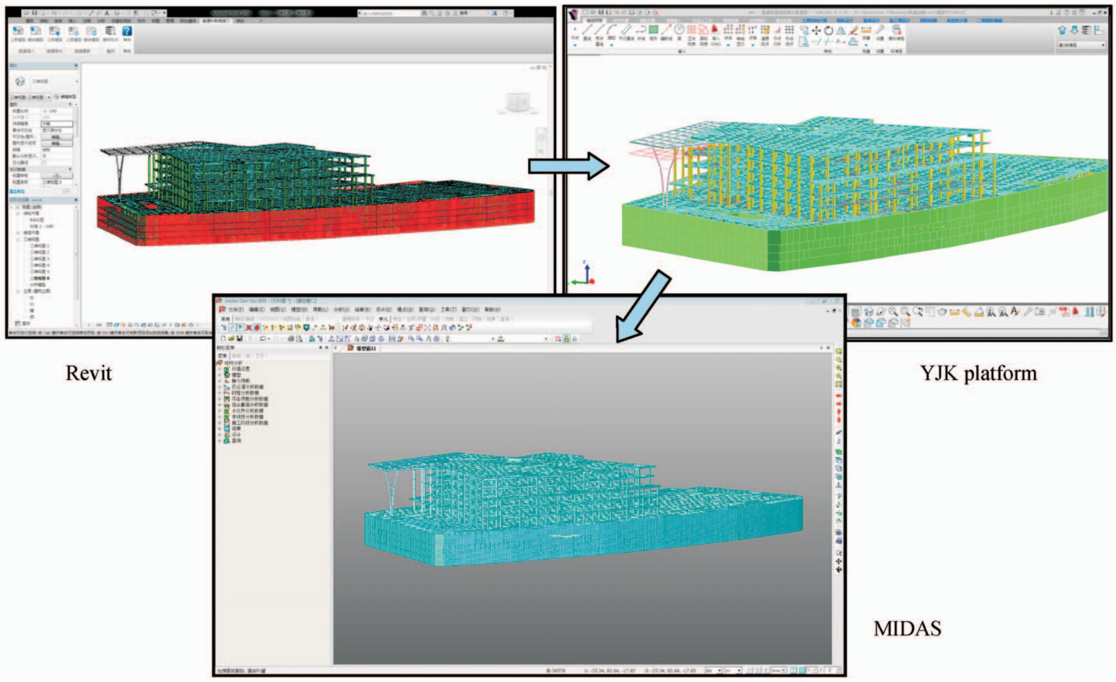

Figure 6. Data transfer from BIM tool (Revit) to MIDAS.

tures to demonstrate the application of interface. It shows that the proposed method achieves higher efficiency for the data transformation through the use of interface. In addition, a few explanations about the Revit interface are as follows.

(1) Compared with geometrical information, only a little non-geometrical information can be exchanged, such as material, section properties, constraint rule, etc. In addition, to improve the accuracy of data transfer and reduce technical difficulty, the eccentricity connec-

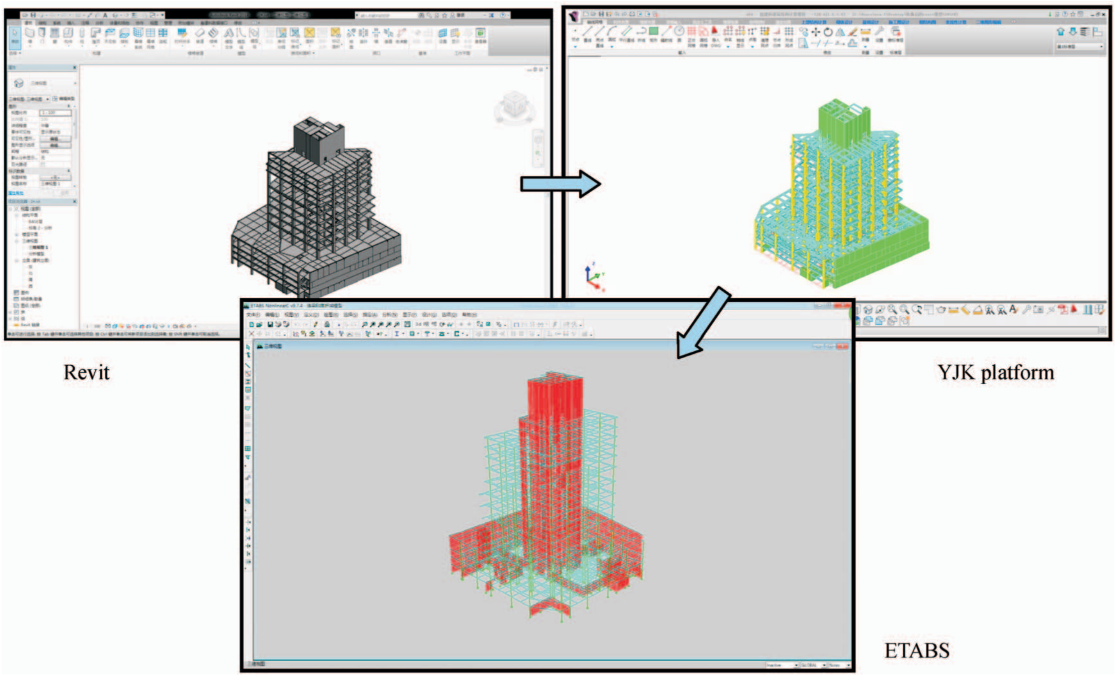

Figure 7. Data transfer from BIM tool (Revit) to ETABS.

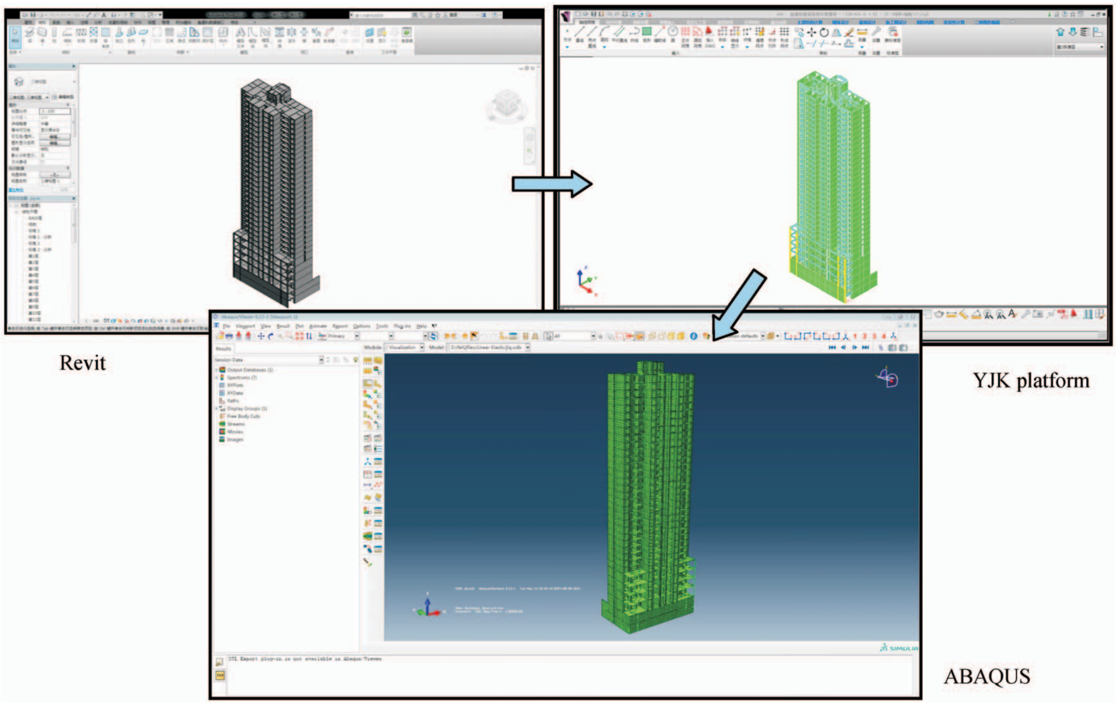

Figure 8. Data transfer from BIM tool (Revit) to ABAQUS.

tion of structural members is not considered.
(2) Four types of materials including steel, concrete, brick, and lightweight aggregate concrete can be exchanged.
(3) Three modeling methods of structural storey that are supported by YJK can be exchanged including standard storey, spatial storey, and broad storey, which are often adopted for the modeling of complex structures.
(4) Four types of cross sections of bar members (such as beam, column, and inclined brace) can be exchanged including rectangular section, variable section, I-steel section, and steel-concrete pipe section (see Figure 9).
(5) Most of the structural openings can be exchanged successfully, and only the standard wall of Revit wall families and two types of slabs can be exchanged (see Figure 10).

6. Discussion and Conclusions

As a logical successor to the traditional CAD, BIM not only represents a digital model, but also a processing technology of data and information. Due to the complexity of BIM, there is still a long way to go for its deep application in the AEC industry. When the information integrating and sharing is realized successfully among different participants involved across the whole building lifecycle, the real values of BIM can be achieved.

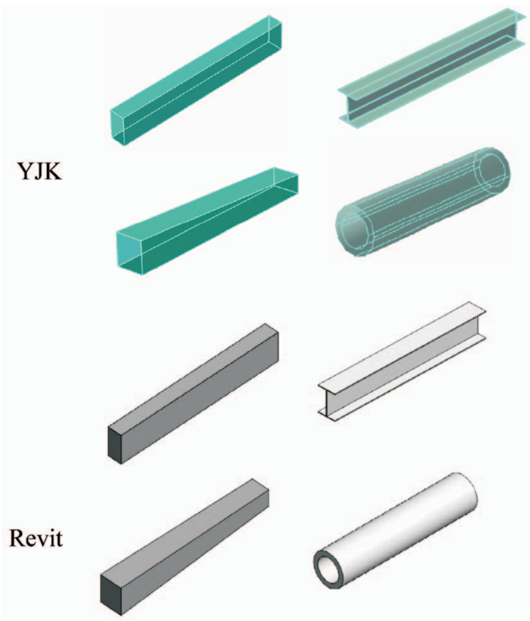

Figure 9. Types of cross sections of bar members.

The structural analysis model plays an important role in the structural design stage. Data and information produced by this step is the main reference for the downstream construction drawing design. Linking structural analysis model with BIM contributes to realizing the information integrating and sharing between structural engineering and other disciplines involved.

Structural engineers often adopt different analysis software applications to create structural model. The data formats of many analysis software applications are totally different from the IFC-format BIM model. Moreover, the BIM model is still in the improving stage and includes plenty of geometrical and non-geometrical information. As a result, establishing a direct method for data transformation between BIM model and structural analysis model is difficult and complicated.

In this paper, the roles of BIM are simply discussed from four aspects through comparing with the traditional CAD. The conformation of BIM structural model and its advantages are summarized. On the basis of Revit and YJK (a Chinese structural design software), the data transformation methodology from BIM model to structural analysis model is analyzed, and an indirect method is proposed by developing a Revit interface. By using an integrated framework of interfaces, the BIM model can be transferred into analysis software applications including MIDAS, ETABS, and ABAQUS. The case study shows that the proposed method is one of the effective ways for realizing data transformation from BIM model to structural analysis model. Compared with the general method, some merits and demerits of the proposed method are shown in Figure 11.

It is necessary to point out that this research is a preliminary effort for data transformation from BIM model

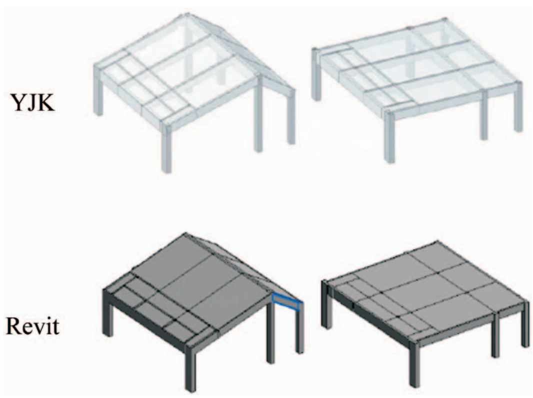

Figure 10. Types of slabs.

Method	Merits	Demerits
BIM Model - Analysis Model (general method)	(1) a direct way. (2) one-to-one model transfer often achieves higher efficiency.	(1) the large differences of data format between two models often lead to difficult data transformation. (2) lots of structural connected nodes need to be modified. (3) the change of software version often affects the model transfer quality. (4) the redundant data of IFC-format files often causes lower transfer efficiency. (5) lots of modifications are required to optimize the transferred model.
BIM Model - YJK Model- Analysis Model (Proposed by this research)	(1) the need to consider the software version change is reduced greatly. (2) compared with the BIM model, it is easier to achieve data transformation from YJK model to analysis model. (3) due to taking the YJK as a platform, it does not need to consider the differences between BIM model and structural analysis model. (4) due to taking an algorithm of ASCII codes, the redundant data of IFC-format files is reduced greatly, and the data transfer efficiency is improved as well. (5) the function of "one model, multiple uses" is supported since YJK has achieved model transfer with most analysis software applications.	(1) an indirect way. (2) Multiple transformation interfaces need to be developed.

Figure 11. A comparison table between general method and proposed method.

to structural analysis model. The adopted method is dependent on Revit and YJK, and only geometrical information and a little non-geometrical information can be exchanged. In the next step, the authors will develop a neutral interface for the bidirectional data transformation between BIM model and structural analysis model. Since both data formats are very complicated, there are still lots of works to do.

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