

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**SCHOOL OF CIVIL AND ENVIRONMENTAL**  
**ENGINEERING**



**Application of BIM Using Revit and Other  
Conventional Structural Design Software: A  
Case Study on A High-Rise Building**

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**A Thesis in Structural Engineering**

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June 2019

Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled ‘**Application of BIM using Revit and Other Conventional Structural Design Software: A Case Study on a High-Rise Building**’ presented by **Eyosias Dawit**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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## **UNDERTAKING**

I certify that research work titled “Application of BIM using Revit and Other Conventional Structural Design Software: A Case Study on a High-Rise Building” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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## **ABSTRACT**

Building information modeling or BIM is a workflow whose application on a construction project will enable all involved players to compile information on every aspect of the building in a central model/database. Through BIM adoption, the entire building can be virtually built on a computer. This research examines the experiences of some countries with BIM and use that insight to introduce BIM to Ethiopian design and construction industry. BIM touches every part of a building's life cycle starting from the design phase well into the construction phase and beyond that into asset management. However, the research will focus on the design stage of a building. Adaptation of BIM during design stage will require all design team members to implement BIM. The research focuses on structural designers and how BIM can improve the quality of their design. The research demonstrates how all structural design activities can be integrated with each other and how cross-discipline collaboration with architecture can be achieved through BIM adoption. A sample building is taken and BIM is implemented using Revit along with conventional software package ETABS and SAFE. plugins and applications have been developed for all these software packages to facilitate interoperability amongst them so that they can act as a single platform. Modeling, analysis, design and clash detection were all facilitated by applying BIM. Through the research various benefits of BIM were illustrated.

**Keywords. BIM, Integration, Interoperability, Design**

## **ACKNOWLEDGMENTS**

The author would like to thank his advisor, Dr. Bedilu Habte, for his support and guidance throughout the thesis work. His advice, encouragement and feedback are deeply appreciated by the author.

Addis Ababa institute of technology and Ethiopian road authority provided the postgraduate program opportunity and the author duly acknowledges that. He is also grateful for the continued support of his family and friends.

## TABLE OF CONTENTS

<b>ABSTRACT.....</b>	<b>IV</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>V</b>
<b>TABLE OF CONTENTS .....</b>	<b>VI</b>
<b>LIST OF TABLES.....</b>	<b>IX</b>
<b>LIST OF FIGURES.....</b>	<b>X</b>
<b>CHAPTER 1 INTRODUCTION .....</b>	<b>1</b>
1.1 Background.....	1
1.2 Statement of the Problem.....	2
1.3 Objectives of the Research.....	4
1.4 Scope of the Research .....	4
1.5 Method .....	4
1.6 Organization of the thesis .....	5
<b>CHAPTER 2 LITERATURE REVIEW .....</b>	<b>6</b>
2.1 What is BIM? .....	6
2.1.1 Definition of BIM .....	6
2.1.2 Common misconceptions about BIM .....	6
2.1.3 Geometric Vs Parametric Modeling .....	7
2.1.4 Common BIM Software Packages.....	8
2.2 The Status of BIM Adoption in Some Nations .....	9
2.2.1 BIM in Africa .....	10
2.2.2 BIM in Asia .....	11
2.2.3 BIM in North America.....	14
2.2.4 BIM in South America.....	16
2.2.5 BIM in Australia .....	17
2.2.6 BIM in Europe .....	18
2.2.7 BIM in Middle East .....	21
2.2.8 Summary.....	22

2.3	BIM for structural engineers .....	24
2.3.1	Benefits of BIM .....	24
2.3.2	Clash detection.....	26
2.3.3	BIM and Interoperability Issues .....	27
<b>CHAPTER 3 APPLICATION OF BIM PART I: PREPARING MODEL.....</b>		<b>29</b>
3.1	Introduction.....	29
3.2	Selecting BIM Package.....	29
3.3	Creating the Analytic Model.....	31
3.4	Defining Project Information Parameters .....	33
3.4.1	Geotechnical information .....	33
3.4.2	Structural information.....	34
3.5	Defining Materials in BIM.....	35
3.5.1	Identity .....	35
3.5.2	Physical Property .....	35
3.6	Structural Objects in BIM.....	36
3.6.1	Data Organization and Revit Object Hierarchy.....	38
3.6.2	RC Beam Family .....	40
3.6.3	RC Column Family.....	41
3.6.4	Structural Wall Family .....	43
3.6.5	Structural Floor Family.....	45
3.6.6	Foundation Families .....	45
3.7	Stories in BIM.....	48
3.8	Load case and Load combination in BIM.....	49
3.9	Exporting Model for Structural Analysis.....	49
<b>CHAPTER 4 APPLICATION OF BIM PART II: ANALYSIS, DESIGN AND CLASH DETECTION.....</b>		<b>54</b>
4.1	Introduction.....	54
4.2	Analysis Results.....	54
4.2.1	Modal Response Spectrum Analysis .....	55
4.2.2	Inter-story Drift Sensitivity Coefficient.....	56

4.2.3	Damage Limitation Requirement .....	56
4.2.4	Determining Structural Regularity .....	57
4.3	Foundation Analysis and Design .....	61
4.5	Clash Detection .....	62
4.6	Preparing Construction Drawing .....	66
<b>CHAPTER 5 INTEROPERABILITY AND DEVELOPMENT OF TOOLS &amp; PLUGINS</b>		<b>70</b>
5.1	Development of Tools and Plugins .....	70
5.2	Bridging ETABS and Revit .....	71
5.2.1	SBIM File Type .....	72
5.3	Developing ETABS Tools for BIM Implementation.....	72
5.3.1	ETABS Tool Development Workflow .....	73
5.3.2	The ETABS Tools .....	77
5.4	Developing SAFE Tools for BIM Implementation.....	118
5.5	Developing Revit Plugin for BIM Implementation .....	121
<b>CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS</b> .....		<b>125</b>
6.1	Conclusions .....	125
6.2	Recommendations .....	126
<b>REFERENCES</b> .....		<b>128</b>
<b>APPENDIX A: REVIT STRUCTURAL FAMILIES AND THEIR PARAMETERS</b> .....		<b>133</b>
<b>APPENDIX B: LIST OF IMPORTANT PROGRAMMING CODES</b> .....		<b>142</b>

## LIST OF TABLES

Table 1: Dimensions of BIM (BIM Academy, 2017).....	7
Table 2: Detected clashes between building objects .....	66
Table 3: Parameters created for project information system family.....	133
Table 4: RC Beam family parameters .....	134
Table 5: RC Column family parameters.....	135
Table 6: Parameters created for wall system family.....	136
Table 7: Parameters created for floor(slab) system family.....	139
Table 8: Parameters created for foundation slab system family.....	140
Table 9: Parameters created for story system family.....	141
Table 10: Code from ETABS plugin source codes: Direct ETABS access .....	143
Table 11: Code from ETABS and SAFE tools source code: Using ETABS/SAFE output files .....	148
Table 12: Code from Revit plugin source code .....	149

## LIST OF FIGURES

Figure 1: Geometric and building data models.....	8
Figure 2: Architectural model of the sample project.....	32
Figure 3: Central model with only the structural element visible .....	33
Figure 4: Data on a beam object: pre-analysis.....	37
Figure 5: Additional Data on a beam object: post-analysis.....	37
Figure 6: Additional data on a beam object: post-design .....	38
Figure 7: Revit object hierarchy illustration.....	39
Figure 8: Example of flow of data in Revit hierarchy .....	40
Figure 9: Some RC column family parameters .....	42
Figure 10: Additional RC column family parameters .....	42
Figure 11: Some pier wall parameters (a) Section view (b) Elevation view .....	44
Figure 12: Some spandrel wall parameters (a) Section view (b) Elevation view.....	44
Figure 13: Some floor system family (RC slab) parameters .....	45
Figure 14: Foundation slab family parameters .....	47
Figure 15: Further foundation slab family parameters .....	47
Figure 16: Some level system family structural analysis parameters.....	48
Figure 17: The analytic model in Revit .....	50
Figure 18: The analytic model in ETABS .....	51
Figure 19: The foundation objects in SAFE.....	52
Figure 20: Interaction of software packages for foundation design .....	61
Figure 21: Beam to windows collusion. (a) Initial orientation, (b) Collusion after analysis and design, (c): Collison resolved .....	64
Figure 22: Lift shaft to column collusion. (a) Initial orientation, (b) Collusion after design, (c) Collison resolved.....	65
Figure 23: 3D view of isolated footing reinforcement .....	69
Figure 24: ETABS tool's general flowchart.....	74
Figure 25: Story data extraction flowchart .....	79
Figure 26 Inter-story drift sensitivity coefficient computation flowchart .....	80
Figure 27: Damage limitation verification flowchart .....	81
Figure 28: Plan regularity verification flowchart .....	82
Figure 29: Elevation regularity verification flowchart .....	83
Figure 30: Additional elevation regularity verification flowchart.....	84

Figure 31: Story data manager tool GUI: Data extraction.....	85
Figure 32: Story data manager tool GUI: Inter-story drift sensitivity coefficient computation .....	86
Figure 33: Story data manager tool GUI: Regularity in plan regularity.....	87
Figure 34: Story data manager tool GUI: Regularity in elevation.....	88
Figure 35: Modal Analysis Manager tool flowchart: defining response spectrum load cases .....	93
Figure 36: Modal Analysis Manager tool flowchart: Defining load combination .....	94
Figure 37: Modal Analysis Manager flowchart: Checking modal mass participating ratios .....	94
Figure 38: Modal analysis tool flowchart: Verifying base shear.....	95
Figure 39: Modal analysis management tool GUI: Creating response spectrum load cases .....	96
Figure 40: Modal analysis management tool GUI: Creating response spectrum load combinations.....	97
Figure 41: Modal analysis management tool GUI: Checking modal analysis conditions	98
Figure 42: Wall Analysis and Design Manager tool flowchart .....	100
Figure 43: Wall Analysis and Design Manager tool GUI .....	101
Figure 44: Example of a beam group .....	103
Figure 45: Beam design manager tool flowchart.....	105
Figure 46: Beam Design Manager tool GUI.....	107
Figure 47: Column design manager tool flowchart .....	109
Figure 48: Column Design Manager tool GUI.....	111
Figure 49: Slab Analysis and Design Manager tool flowchart.....	113
Figure 50: Slab Analysis and Design Manager tool GUI.....	114
Figure 51: Frame design forces manager tool flowchart .....	116
Figure 52: Frame Design Forces Manager tool GUI.....	117
Figure 53: Foundation analysis and design manager tool flowchart .....	119
Figure 54: Foundation Analysis and Design Manager tool GUI.....	120
Figure 55: Import Data tool flowchart.....	122
Figure 56: Import Data GUI .....	124

## CHAPTER 1 INTRODUCTION

### 1.1 Background

During the life span of a building projects, several professionals across various disciplines gather together to make their contribution. Even the design phase alone sees multiple disciplines collaborating. Structural engineers need to collaborate with architects, sanitary engineers, electrical engineers and other professionals in a design team. They also need to engage with non-technical players.

Traditionally, these professionals work in disconnected manner. Each of them produces large amount of information and communicate, for most part, through 2-D drawings. Different software packages are used by the diverse group of professionals. As a result, the design phase is plagued with fragmented works, data loss, unnecessary reworks, miscommunications, limited visualization and more. The fact that the design phase often comprises modifications and revisions further exasperate the problems. Thus, the design phase and the engineers involved in it can benefit from a powerful technology that can revolutionize the entire process. That technology is Building Information Modeling (BIM).

BIM is a process in which various professionals and players are working cooperatively and sharing information efficiently to deliver a more efficient design and construction process (François Denis; AIA research team, 2015). The workflow covers the entire life span of a building project, creating, coordinating, documenting, managing and updating information about every aspect of the building. (Matarneh & Hamed, 2017)

BIM extends the traditional CAD approach by defining and applying intelligent relationships between the numerous building elements (structural and non-structural elements) of a building (Singh, Gu, & Wang, 2011).

Through BIM, a virtual representation of a building containing both graphic and non-graphic information is created (Nielsen & Madsen, 2010). This final product of BIM will be a model that is data-rich, intelligent and parametric digital representation of a building or infrastructure (Sampaio, 2017). By adopting BIM, a design team is able to virtually build a given structure on a computer long before ground is broken at construction site.

The thesis outlines the workflow for implementation of BIM in a sample G+12 Mixed-use building. Moreover, the thesis examines the benefits and challenges of BIM implementation for a structural engineer during modeling, analysis and design tasks.

BIM is not a software; rather, it is a process that is implemented through multiple software packages operating as a single platform. Revit, a powerful BIM packages, along with conventional structural analysis package ETABS and SAFE are used for the research. Interoperability among these tools has a paramount importance for successful BIM adoption. Plugins and applications are programmed as part of the research to facilitate interoperability.

## **1.2 Statement of the Problem**

### **Lack of Integration**

Professionals across multiple disciplines get involved in the design phase of a building project. After the architect generates the building's form, structural engineers will use that form to create a structural model. Sanitary engineers and electrical engineers also make their contribution. Each professional conduct their work disjointedly. This disconnected workflow creates myriads of problems, such as:

Hindered collaboration: Since there is no common database for all disciplines, collaboration is done manually and, mostly, using 2-D drawings. Sharing of information is prone to data loss. When modifications and revisions are made, they need to be manually tracked and managed.

Limited visualization: Real world buildings are an integration of all building elements (structural, architectural, sanitary, electrical, etc.). Thus, unless models from all disciplines are integrated into a single model, the final model cannot be considered a real-life representation of the building.

Unnecessary rework: Traditionally, structural engineers recreate the architectural model as a structural model. This is basically transcribing information from an architectural software into a structural software. No new information is produced rather information is duplicated. The more complex the building is the more time wasted recreating existing information. Similarly, when construction drawings are created, large amount of information is recreated as compared to the new information created.

Clashes and clash related costs: Traditionally structural designers and the rest of the design team members present their work in separate 2-D drawings. Trying to manually detect cross discipline clashes using unconnected 2-D drawings is difficult. Conflicts are most likely to be left undetected and discovered after construction begun. This leads to construction stalling and reworks that incur additional cost.

### **Interoperability issues**

For successful data integration and BIM implementation, the software packages used by structural engineers should be able to successfully exchange data with BIM packages. Since the BIM packages are used as a common database for all professions, data exchange with the packages is paramount for cooperation among disciplines.

The software packages do come with some capability of data exchange. However, they do not comprise exchange of the vast amount of structural analysis and design data that is generated by structural analysis tools. Thus, a data island is created where vast amount of important structural data is separated from the common database.

### **1.3 Objectives of the Research**

Through the research, BIM is implemented on a G + 12 Mixed-use building. Structural design is integrated with architectural design through a common database. Structural object templates that are capable of storing structural analysis and design data are created. Design activities that used to be done outside ETABS are integrated with ETABS through the development of tools and plugins.

The interoperability issue is mitigated by programming plugins and tools. Through these plugins and tools, the BIM package is integrated with the structural design tools.

### **1.4 Scope of the Research**

The scope of the research is the adoption of BIM during the design stage of a building project. Specifically, it focuses on the structural engineers' role during BIM implementation and demonstrate how they can successfully adopt BIM on their work.

The research is limited to the cross-discipline collaboration of structural engineering with architecture. The research does not cover post design tasks.

### **1.5 Method**

The research commences with a review of various materials related to BIM adoption. The experience of countries that have adopted BIM or attempting to adopt BIM is explored. Their experience is used to understand BIM implementation better and to anticipate the possible challenges that may arise. The meaning of BIM and its features with regard to structural engineering is discussed.

The implementation of BIM is demonstrated on a G+12 Mixed-use building. A central model that also serves as a central database is prepared using Revit. This model is then exported to ETABS and SAFE for structural analysis and design. The result is then imported back to Revit for further data manipulation like preparing construction drawings, clash detection, etc. A huge amount of structural data is produced and stored on the central model/database.

Through the stages briefly discussed on the previous paragraphs, many powerful features of BIM are explored. The real-life advantage of these features in relation to cost, time and productivity is be outlined.

Applications and plugins are developed to help with the interoperability of the BIM tool with structural design tool.

## **1.6 Organization of the thesis**

The thesis is organized into six chapters. The first chapter presents a brief introduction of BIM followed by the statement of the problem, the objective and scope of the research and the method employed to conducted the research.

The second chapter presents a review of previous researches concerning with the various features of BIM and the experience of some countries with BIM.

The third chapter presents the adoption of BIM during the structural modeling phase of the design stage. This is done using the G+12 sample building.

Chapter four continues from chapter three by presenting the adoption of BIM during and after structural analysis and design. The important subject of clash detection is incorporated in this chapter.

Chapter five discusses how plugins and applications were programmed to expand the capability of the design packages and solve the interoperability issues among the BIM package and the design packages.

Chapter six presents conclusions and recommendations for future studies.

## CHAPTER 2 LITERATURE REVIEW

### 2.1 What is BIM?

#### 2.1.1 Definition of BIM

BIM, which is the acronym for building information modeling, is a process in which different stakeholders and professionals are working together and exchanging information to provide a more efficient design and construction process (François Denis; AIA research team, 2015). It is a process that covers the entire lifecycle of a building and it can create, coordinate, document, manage and update information about the building (Matarneh & Hamed, 2017). Through the BIM process a virtual prototype of a building can be developed (François Denis; AIA research team, 2015).

The adoption of BIM on a building project results in a more integrated design and construction process and a better quality of building at lower cost and reduced project duration (Eastman, Teicholz, Sacks, & Liston, 2011).

#### 2.1.2 Common misconceptions about BIM

The word ‘Building’ in Building information modeling, might mislead some people into believing BIM is for buildings only. However, the BIM workflow can be implemented in the design, construction and facility management of all forms of infrastructures (Bartley, 2017).

Another misunderstanding arises from the word ‘Modeling’. Some might believe that BIM is synonymous to simply generating 3D model of a structure. However, BIM usage goes beyond a 3D model. BIM will provide a wide range of applications throughout the life cycle of projects. It combines the 3D model with parametric design, coordination, communication and visualization (Eastman, Teicholz, Sacks, & Liston, 2011). These applications are sometimes referred to as “dimensions”. (BIM Academy, 2017) The dimensions starting from 4D are listed on Table 1.

**Table 1: Dimensions of BIM (BIM Academy, 2017)**

<b>BIM Dimension</b>	<b>Remark</b>
<b>4D BIM</b>	<ul style="list-style-type: none"><li>• Construciton sequencing</li><li>• Adds or links a time schedule to a 3D model</li><li>• Improves planning and controling of construciton</li></ul>
<b>5D BIM</b>	<ul style="list-style-type: none"><li>• Add cost related information to the 4D model</li><li>• Estimating and managing costs along with procrument</li><li>• Assists in visualizing the progress of project activities along with the associated costs</li></ul>
<b>6D BIM</b>	<ul style="list-style-type: none"><li>• Tackles sustainability</li><li>• Informaiton such as energy use, resource efficiency are aded to the model</li></ul>
<b>7D BIM</b>	<ul style="list-style-type: none"><li>• Integrates information regarding facility management to the model</li></ul>

### **2.1.3 Geometric Vs Parametric Modeling**

While CAD technology is limited to geometric data, BIM models include both geometrical and non-geometrical data (Singh, Gu, & Wang, 2011). Through BIM technology, a parametric model which allows extraction of 2-D drawings, documentations and element's attributes & specifications is created.

Figure 1 presents the difference between the two modeling. As it can be seen, while the geometric representation presents the wall as a rectangle with origin point, the parametric representation provides more intelligent information. Information such as usage, material, cost and so on are represented in the parametric model.

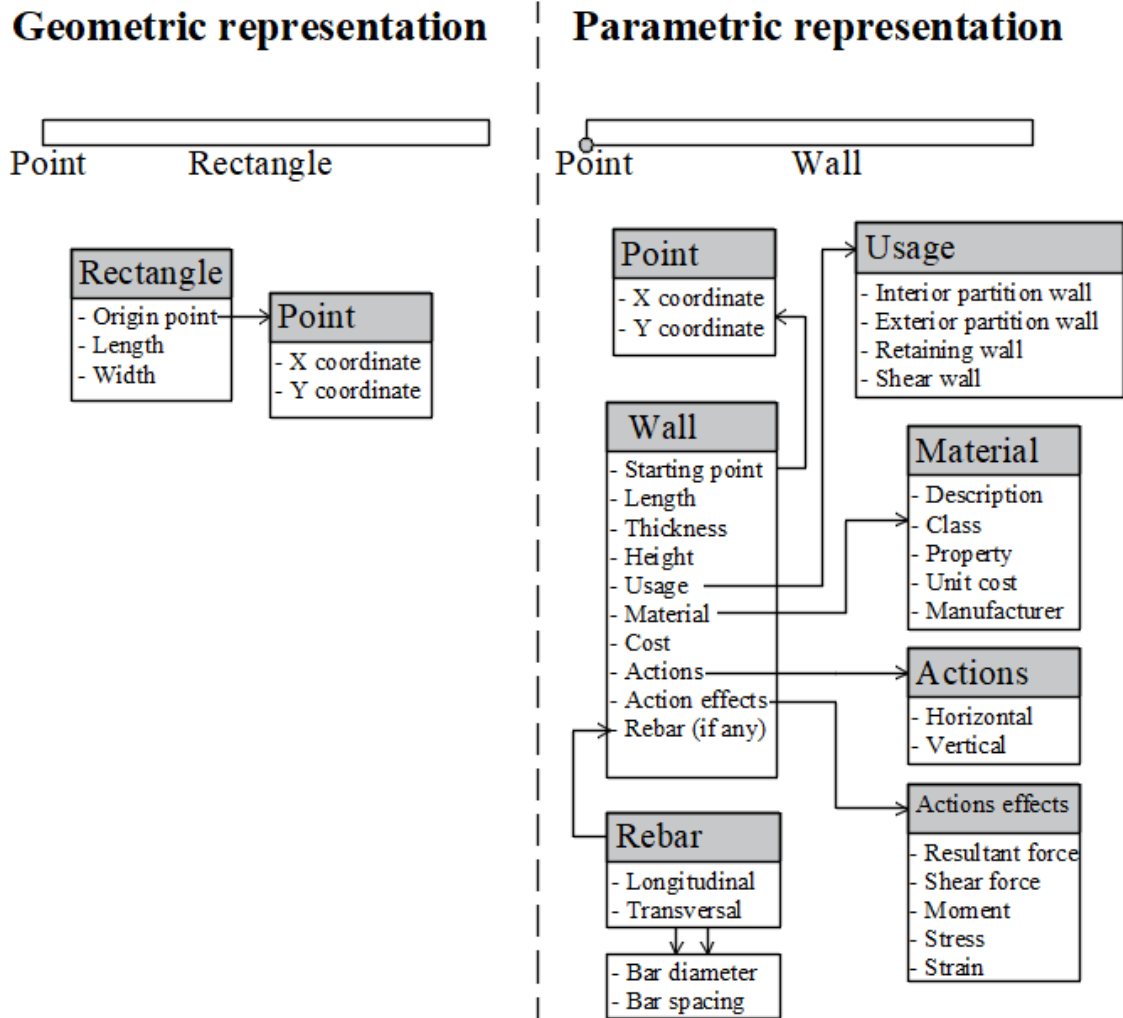


Figure 1: Geometric and building data models

#### 2.1.4 Common BIM Software Packages

Several BIM software packages are available. Eastman et al. (2011) listed and discussed some of these BIM platforms. The discussion included Revit, Bentley systems, ArchiCAD, Digital Project, Vectorworks, Tekla Structures, DProfiler and AutoCAD-based applications. The authors explained the strength and weakness of these platforms.

Eastman et al. (2011) stated that Revit was the best-known and the market leader for BIM implementation in architecture. On Section 2.2 of this thesis, where the BIM experience of some countries was discussed, it was evident that Revit is a popular BIM package.

B.M McGuire (2016) studied six BIM tools to use on a research. The goal was to present “a method and prototype implementation to apply BIM software to the operation and maintenance stage of bridge’s service life”. The tools considered were Graphisoft ArchiCAD, Tekla Structure, Midas Civil, Bentley LEAP Bridge, Autodesk Revit and Autodesk BIM 360 Field. After comparing these six BIM tools, the researcher decided that Autodesk Revit was the most robust BIM tool. (McGuire, 2016)

## **2.2 The Status of BIM Adoption in Some Nations**

To have a better understanding about the application of BIM along with its benefits and challenges, the experience of nations that implemented or attempting to implemented BIM was studied. It is true that BIM adoption experience cannot be simply transferred from one country to another. The economic and technological state of countries affects the implementation of BIM. However, experience from other countries can be used as pathway to effective BIM implementation. Thus, some countries from across the world were selected and their experience with BIM is reviewed and presented under this section.

As the research is focused on the implementation of BIM from the point of view of structural engineers, the materials reviewed were only the ones that involved civil or structural engineering aspects.

During the review of BIM implementations on the selected countries, the following points were given focus.

- How was design and construction affected by the implementation of BIM
- What were the challenges of BIM implementation?
- How could the challenges be overcome?

## **2.2.1 BIM in Africa**

### ***2.2.1.1 BIM in South Africa***

South Africa first embraced the BIM technology in the AEC sector during construction activities for FIFA 2010 World Cup. (Ogwueleka & Ikediashi, 2017). In 2016, BIM institute carried out a survey in South Africa to understand the view of clients, architects and engineers regarding BIM. The survey included participants from all threads of design and construction related professions including engineering. (Harris, 2016).

Harris (2016) conveyed that the most reported benefit of BIM was better team collaboration (76%) followed by improved productivity (68%). Other benefits such as shorter project schedules and lower project costs were also reported. However, the survey also revealed that clients do not seem interested in BIM. The reason for this, given by the author, is the lack of BIM related studies in South Africa. (Harris, 2016)

### ***2.2.1.2 BIM in Nigeria***

Fadason, Kaduma, & Chitumu (2018) carried out a research targeting Nigerian building design firms to discuss the challenges of BIM implementation in Nigerian construction industry. Structural/civil engineers were among the respondents of the questioners prepared for the research.

The study showed that among the respondents, engineers are the most users of BIM (44.4%). According to the authors, BIM implementation in Nigeria is still in infancy stage. More than half the participants (59.7%) have under 5-year experience with BIM while 23.6% have none at all.

Fadason, Kaduma, & Chitumu (2018) concluded from their study that the very significant challenges of BIM implementation in Nigeria are lack of BIM education and lack of information on BIM. More challenges identified by the study include lack of investment in BIM, lack of government support (perhaps through legislation), lack of guide and hesitation to learn new workflow.

The participants also forwarded their opinion regarding the possible approaches to overcoming the challenges. Some of their suggestion were increasing research on BIM in higher learning institution, conduction BIM skill development programs, and developing adequate infrastructure to support BIM implementation. Improving interoperability of BIM software packages within existing tools is also suggested as a possible solution.

### **2.2.1.3 BIM in Cameroon**

Abanda et al. carried out a study to explore BIM implementation in Cameroon. The result of their study reviled that 30% of firms implementing BIM were engineering firms. The BIM tool that was very popular among the participants were Robot Structural Analysis. (Abanda, Manjia, Pettang, Tah, & Nkeng, 2016)

The study uncovered that most professionals implemented BIM for structural analysis and structural design purposes. Speed, high quality outputs and high performance are the three most popular responses of the participants when asked why they use BIM. The researches argue that countries with increasing BIM implementation often have government policies that encourage use of BIM in projects.

### **2.2.2 BIM in Asia**

Ismail, Chiozzi, & Drogemuller carried out a study to shine some light on how BIM is evolving in some Asian countries. The Asian countries considered during their research were China, India, Malaysia, Indonesia, Thailand, Myanmar, Sri Lanka, Mongolia, Vietnam and Pakistan. On their paper, the authors write that while most of the developing countries had low level of BIM implementation, the benefits of BIM are acknowledged in those countries. (Ismail, Chiozzi, & Drogemuller, 2017)

The authors believe government mandates could create a surge in the implementation of BIM in those countries. However, the authors also fear that government mandates could sideline the voluntarily implementation of BIM by companies and individuals.

### **2.2.2.1 BIM in China**

Bo et al. conducted a study to assess the BIM implementation in China. The study begins by reviewing the history, strategy, policy and standards related to BIM within China. Even though China do not have a national unified strategy on BIM, Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) have released some documents to encourage BIM implementation. Moreover, some provinces have drafted some BIM promoting policies. (Bo, Khan, Vian, & Zhijun, 2015)

Their study includes 30 projects that claimed to have implemented BIM. The result showed that many who implemented BIM did so on both design and construction stages of the project. Additionally, the result also revealed that among the tools available for BIM implementation, Autodesk Revit was the overwhelming choice. Some of the benefits of BIM mentioned by the project teams included reduction of errors and omissions in construction documents, better design solution and improved coordination between design and construction tasks. The researches acknowledge that the policies that were put in place by the government to encourage BIM uptake were fruitful.

### **2.2.2.2 BIM in Singapore**

Singapore is considered as an advanced implementer of BIM as they pursued to advanced BIM development in 2015 (Sielker & Allmendinger, 2018). The building and construction authorities of Singapore implemented the BIM roadmap in 2010 by targeting to use BIM widely by 2015. (Building and Construction Authority, 2011)

The Singapore BIM Guide Version 2 (Building and Construction Authority, 2013) is part of the Singapore's effort to clarify the requirements of BIM implementation at various stages of a project. This guide provides an outline of the various possible deliverables, processes and professionals involved in construction projects. It includes BIM specifications, BIM Modeling and collaboration procedures. (Edirisinghe & London, 2015)

The Singapore BIM Guide Version 2 identifies the deliverables to be expected of BIM implementation. It identifies the BIM elements and organizes them into disciplines one of which is structural discipline. The guidelines include structural modeling. These guidelines divide the structural modeling activity into various stages. And for each stage of structural modeling, the elements involved and the modeling guidelines are given. (Building and Construction Authority, 2013)

Cross-disciplinary model coordination is major part of BIM implementation. The Singapore BIM Guide addresses this subject by putting forwards recommendation that prevent data loss and errors while sharing data.

### ***2.2.2.3 BIM in Malaysia***

While many engineering firms in Malaysia are aware of BIM technology, only few are implementing it (Nor & Grant, 2014). Memon et al. (2014) conducted a survey with 95 participants to evaluate the current status of BIM implementation in Malaysian construction industry. The benefits of BIM, identified by the study, included improved scheduling, improved drawing coordination and improved work quality. The main obstacle mentioned was lack of awareness of BIM technology.

There is, according to Memon et al. (2014), a lack of competent staff who are able to operate BIM packages effectively. Acquiring the BIM software packages at reasonable cost is also cited as a barrier to BIM implementation. Other barriers that were revealed by the study includes difficulty to learn, not being willing to distort current operational structure and no enforcement to implement the technology

The participates in Memon et al. (2014)'s study believe training of stuff in BIM technology and introducing BIM in university curriculum is a possible strategy to raise awareness about the technology. Supporting BIM uptake through government legislation was also cited as a possible strategy by the participants.

#### **2.2.2.4 BIM in India**

In the years 2013-14, a research was conducted in India by RICS School of Built Environment, Amity University and KPMG to understand how infrastructure developers, architects, engineers and contractors are adopting, implementing and deriving value from BIM (Sawhney, et al., 2014).

Sawhney, et al. reported that a quarter of the respondents reported BIM usage while a little more people are aware of it. Among the organization using BIM, the second largest users were structural engineering consultants only surpassed by architectural firms. (Sawhney, et al., 2014)

The study found out BIM in India is mostly being used during design and development stage of project (80% of respondents) followed by the construction stage (60 % of respondents). The professionals found BIM to be most valuable for improving coordination (86.5%), detecting clash (81.1%) and reducing waste and measuring quantity along with controlling cost. The popular BIM tool in India, according to Sawhney et al. (2014), is Autodesk Revit (79.2%).

The challenges to BIM implementation in India that were mentioned by Sawhney et al. (2014) included, resistance to change, lack of specialists and resource, compatibility between software packages and no mandate from government. The respondents suggested that education and training for BIM implementation, behavioral change from all stakeholders and development of national standards and guidelines are necessary for the future of BIM.

#### **2.2.3 BIM in North America**

##### **2.2.3.1 BIM in Canada**

To grasp the implications of introducing BIM into the Canadian landscape of BIM in research and education, a workshop was held at the École de Technologie Supérieure (ÉTS) in Montreal, Quebec, Canada. The workshop involved BIM trainers, researchers and educators across Canada. (Poirier, Forgues, Staub-Fench, & Newton, 2016)

The workshop recognized the need of BIM related research and education. Experiencing multidisciplinary collaboration & activities was considered to be the biggest need in research and education according to the participants. The participants also suggested “Theory of BIM” should be part of educational curriculum.

The hurdles pointed out by the participants include lack of demand and incentive for BIM implementation, lack of industry understanding and lack of capable staff. The disconnect between academia and industry was also mentioned as a challenge for BIM implementation.

A close coordinate between academia and industry was mentioned as solution to the challenges mentioned. This coordination could be in form of research, study programs and internships. Another proposal made by the participants were more inter-disciplinary education.

### **2.2.3.2 BIM in USA**

General service administration (GSA) had a role in promoting BIM in the US construction industry. It is considered the first organization leading the US government into BIM implementation. It established the national 3D-4D BIM program in 2003. According to Brewer, Gajendran, & Goff, the federal government of US is moving towards BIM enabled building practice. Furthermore, in state and local level, governments are investigating the use of BIM in their project. (Brewer, Gajendran, & Goff, 2012)

Brewer, Gajendran, & Goff conducted four case studies of building projects in US that implemented BIM. The first was a Tsunami warning center. In the project BIM was used to achieve sustainable design. All designers involved in the design team implemented BIM on their task. (Brewer, Gajendran, & Goff, 2012)

The second project reviewed by Brewer, Gajendran, & Goff was a hospital expansion project. On this project BIM was used for design visualizing and coordination. BIM was also considered vital by construction team. As a result of BIM usage, according to the study, the project was completed ten weeks earlier than planned and saved seven million dollars from the allocated fund. The researchers attribute these results to the reduction of redesign and the improved communication among team members due to BIM. Another two projects were also studied on this project and in those projects various features of BIM were used. (Brewer, Gajendran, & Goff, 2012)

Becerik-Gerber & Rice (2010) conducted a survey to assess the perceived value of BIM in the US building industry. The result revealed that BIM was mainly used for visualization, clash detection and building design. The majority of the respondents claimed that due to their BIM uptake, the overall project profitability has increased. Evidently, the more experienced the users became, the more profitability was gained from BIM usage.

The survey further discovered that BIM uptake has cut the cost of projects and their duration. One notable outcome of the survey was that Revit products were the most popular packages for BIM adoption.

## **2.2.4 BIM in South America**

### ***2.2.4.1 BIM in Brazil***

De Almeida & Mello (2017) conducted a study to analyze the organizational culture of construction companies in Niterói, Rio de Janeiro. Their goal was to assess the cultural aspects that must be modified to successfully adapt BIM. Twenty-one local construction companies participated on their study. Among these companies, it was discovered, only 12% knew about BIM technology and made use of it. While 50% of the participants claimed to be aware of the technology but didn't use it.

De Almeida & Mello (2017)'s study further investigated the reason behind the low uptake of BIM. The two most critical reasons provided by the participating companies were lack of time & planning and the resistance of the team to change. The participants also provide reasons that call for BIM adoption. The most important reasons mentioned was market demand and the need for cost reduction and time efficiency. The improved quality of work and competitiveness were also mentioned as the reasons to implement BIM.

The researchers asked the participants what benefit they expect from BIM technology, the answers provided were the decrease in rework, the preparation of precise budget and better reaction to project problems.

Vieira, Clamon, & Cavalcante reviewed 190 Brazilian scientific publication that deals with BIM. The researches admitted that the number of studies in Brazil regarding BIM are increasing. However, they argued that some aspects of BIM were not given sufficient attention. One overlooked issue, according to the researches, is interoperability. The researches recommended that, in the future, more studies should be conducted on data exchange among the software packages used during design and construction. Subjects including creation of applications and plugins were also mentioned as a potential topic to be studied. (Vieira, Clamon, & Cavalcante, 2017)

Vieira, Clamon, & Cavalcante (2017) stressed the need to include BIM technology in the syllabi of architecture and engineering courses and admitted that there are such initiatives in Brazil even if they are isolated.

### **2.2.5 BIM in Australia**

In October and November 2010, a BIM forum was held at three Australian cities (Melbourne, Brisbane and Sydney) and was attended by 35 executives of leading Australian companies comprising, architects' engineers and contractors. (Star, 2010).

The participants recognized the importance of government leadership, through mandate, to boost BIM uptake. Another party that should take the leadership in BIM implementation were the industries involved in the construction industry. The participants discussed and agreed that currently most companies in Australia are at the 3D modeling and collaborative stage of BIM. (Star, 2010)

The benefits of BIM mentioned by the participants include more informed decision making, improved efficiency for design production, real time coordination across disciplines, improved ability for analysis and design audit, quicker client approvals by better presenting design intent, increased return of investment due to better communication and understanding by all involved stakeholders improved risk and opportunity management, higher quality documentation and better quality of information.

Universities do prepare their students for the BIM environment in undergraduate education according the report. This made some graduates to be BIM-ready. The participants, however, suggests the universities should educate students on cross discipline collaboration as well. Even though graduates join the work force with some BIM knowledge, training is required to provide them with workplace experience of BIM. (Star, 2010)

#### **2.2.6 BIM in Europe**

A handbook for the introduction of BIM by the European public sector was prepared by EU BIM task group. The group is a pan-European collaboration that is funded by the European Commission to support Europe's transition to a digital construction sector and in particular introduction of BIM by the European public sector clients and policy makers. (EU BIM Task Group).

The handbook provides public stakeholders with policy, strategic and implementation level recommendations for the introduction of BIM. It contends that there is a window of opportunity for harmonizing European wide common strategic approach for the introduction of BIM. It aims to build common understanding, promote BIM and encourage use of developed standards. (EU BIM Task Group)

Galić et al. (2017) conducted a survey to observe the current state of BIM implementation in four European Countries According to their study, while BIM is being emphasized and developed in scientific and educational circles, it is lacking practical experience in the construction industry of Croatia. The Czech Republic has all the necessary precondition for full BIM implementation since engineers are well aware of BIM due to the availability of information on BIM. However, similar to Croatia, standards and legislations regarding implementation of BIM are lacking

In Slovenia, the benefits and potential of BIM implementation was first identified by academic circles in Slovenian universities. These universities adopted BIM subject into the curricula of their civil engineering study programs. In these Universities, early pilot projects were conducted primarily for research purposes. These projects grabbed the attention of construction companies which resulted in to the expansion of BIM paradigm into Slovenia construction sector. This led to the foundation of the BIM Association of Slovenia, which began with the integration and systematic regulation of BIM in a broader sense. (Galić, et al., 2017)

#### **2.2.6.1 BIM in Germany**

Though, by international comparison, German is relatively behind in BIM implementation, there is a drive towards BIM by the Ministry of transport and digital infrastructure who announced a strategic road map for BIM in 2015 (Sielker & Allmendinger, 2018)

The strategic road map for BIM was designed to facilitate the target that BIM is to be implemented on all new public projects procured in Germany from the end of 2020 (EU BIM Task Group). The strategic map comprises a guiding principle, a hypothesis that describe the anticipated value for Germany and a vision for the German construction industry in the digital age. It provides clarity regarding the future requirements all participants should prepare for. It also gives everybody sufficient time to make the necessary changes by setting the timetable for the gradual introduction of BIM. It helps to recognize and prioritize activities and funding requirement. (Federal Ministry of Transport and Digital Infrastructure, 2015)

According to Galić et al. (2017), a series of BIM pilot projects, has been conducted in Germany. Their purpose is accumulation of knowledge from various projects so that it can be used in similar future projects.

Both (2012) conducted a study on the implementation of BIM in Germany construction industry. The study included architects and engineers among other stakeholders. The study revealed the level of BIM implementation is high. Particularly in the early design stages, BIM is a popular method. These stages include designing and detailing.

#### **2.2.6.2 BIM in UK**

Level 2 BIM or “collaborative BIM” was made mandatory on all public sector projects of UK including delivery of all information and documentation by 2016. (Edirisinghe & London, 2015). This mandate was part of the UK government’s construction strategy 2011. (EU BIM Task Group)

Level 0 BIM is where 2-D CAD files are used for design while Level 1 BIM is where 3-D information is used for design. On Level 1 BIM, design team members will have their own 3-D model but no collaboration. In Level 2 BIM, however, a collaborative environment will be realized. By implementing Level 3 BIM, a project will have a single real-time BIM model. The creation and usage of this model will be shared between the major players of the project. (BIM Academy, 2017)

According to EU BIM task group, the UK government level 2 BIM program supports the achievement of reduction of initial as well as whole life cost of buildings, reduction of project completion time, reduction in greenhouse emissions and reduction of trade gap for construction materials. (EU BIM Task Group)

The UK government invested in a program led by the BIM task group that worked to define BIM and its level of maturity. The group were also undertaking the task of preparing departments for delivery of project using level 2 BIM, defining the learning requirement necessary to prepare the industry for BIM and setting up support communities. The EU BIM Task Group marks the UK task group’s freely available standards and specifications as a good lesson to be learnt. Later, The UK BIM task group shifted its focus to level 3 BIM (The UK BIM Alliance, 2016).

In response to the UK governments Level 2 mandate, an industry alliance was formed and launched on October 2016 (The UK BIM Alliance, 2016). This alliance emerged from BIM communities set up by the UK BIM task group. The focus of this alliance was implementation of BIM level 2 and its purpose was to provide clear guidance for the industry (The UK BIM Alliance, 2016).

A report by the UK BIM alliance states that due to the level 2 BIM mandates, the United Kingdom remains one of the leaders in BIM policies. According to the report. With the task group, alliances and communities, UK has an opportunity in providing a global lead on how to adopt BIM. (The UK BIM Alliance, 2016)

## **2.2.7 BIM in Middle East**

### **2.2.7.1 BIM in Jordan**

Matarneh & Hamed (2017) conducted an exploratory study to understand the level of BIM implementation and to define its perceived value, benefits and challenges in Jordanian construction industry. Architects and engineers including civil engineers and contractors participated in the study.

The study revealed that BIM implementation is a new trend in Jordanian construction industry with 45% of participants saying they used the technology for 2 to 5 years. 65% of the participants stated that they self-taught BIM while 20% of them said they were trained by their company. Only 3% of the participants said they learned BIM by training during college/university. Among the BIM tools, Autodesk products were the most used. 70% of respondents stated that BIM was implemented during the design phase.

The benefits of BIM were outline on the study. 95% of participants believed on BIM's ability to reduce rework and design errors and improve productivity. The respondents also agreed that BIM improves visualization. These benefits are translated in to time reduction and cost minimization. (Matarneh & Hamed, 2017)

BIM's ability to improve collaboration and communication between different project disciplines was also pointed out by the respondents. Other benefits of BIM mentioned by the participants of the study were design review, project documentation, clash detection, cost analysis, shadow analysis and the ability to automatically check design against constraints.

Matarneh & Hamed (2017) went further and investigated the barriers of BIM implementation in Jordan construction industry. Major issues raised by 95% of the participants of the study were lack of government support or incentives or mandate and lack of standards and codes. Other barriers mentioned was the lack of awareness about BIM and its benefits. Lack of demand from client was also mentioned along with the resistance to the radical change BIM will bring to the current workflow and practices. The lack of training was also mentioned as a barrier to BIM implementation.

### **2.2.8 Summary**

During the review of the materials, some important patterns were observed across the countries. By attempting to implement BIM, the countries reaped some common benefits. They also faced common challenges and took or planned to take similar actions to overcome the challenges and enhance BIM implementation.

Advanced users of BIM used it throughout the entire stages of design and construction. Countries that are at the infancy stage of BIM, however, used it during the design stages of projects. The design stage including the structural analysis and design tasks were the most prominent stages where BIM workflow was and is being implemented.

The materials examined mentioned a number of software packages used for BIM implementation. Autodesk's Revit was the popular one.

Some of the repeatedly mentioned benefits of BIM are:

- Better collaboration among design team members (across disciplines) as well as between design and construction team members
- Improved productivity of designer and higher quality of design output
- Better presentation and improved visualization of design output

- Reduction of errors, reworks and omission of important information
- Time reduction, cost minimization, early clash detection and instant cost determination

Most of the challenges of BIM implementation mentioned remained similar across nations. This begs any nation that is thinking to implementing BIM to expect similar challenges. The obstacles that were repeatedly mentioned by the materials reviewed are listed below.

- Lack of BIM and cross-discipline education for engineering students
- Lack competent staff that possess BIM knowledge and skills
- Absence of information, resources and guidelines on BIM implementation
- Absence of demand by clients due to lack of awareness
- Lack of government support and incentives
- Resistance to abandon the current work culture and adopt BIM workflow instead

The more advanced users of BIM have already overcome most of the hurdles mentioned above. Their experience in overcoming these challenges is very valuable for a would-be BIM implementer. In countries, where BIM implementation is at the early age, the researchers probed their respondents to forward possible solution for the challenges mentioned before. Some of the solution that were suggested and already applied to solve the challenges of BIM are discussed below.

- Government support can create a surge in BIM uptake. The government support can be in a form of incentives, mandates, policies and legislations.
- Development of national standards and guidelines also propelled the implementation of BIM forward in the advanced BIM user countries.
- Increasing BIM discussions and studies around academic circles. This comprises introducing BIM in university curriculums. Furthermore, providing interdisciplinary education for engineering students will assist them during cross-discipline collaboration and adopting BIM once they graduate.
- Moreover, Universities can lead the way by conducting pilot BIM projects which can be used as a benchmark by the industry for future projects.

- Developing BIM skill of professionals and all project team members through trainings
- Improving interoperability of BIM software packages with existing tools (design tools for structural engineers)

This research paper is prepared in light of the experiences and recommendations of the countries who employed BIM. It will represent a step towards introducing BIM to Ethiopian design and construction industry. It will focus on the design (Structural) aspect of BIM implementation. It will attempt to provide a benchmark for future studies that should tackle the various aspects of BIM implementation.

## **2.3 BIM for structural engineers**

### **2.3.1 Benefits of BIM**

#### ***2.3.1.1 Improved Collaboration and Communication***

During a life time of a project, professionals from multiple disciplines work cooperatively. Traditionally this collaboration is based on the exchange of 2-D drawings and documents. (Singh, Gu, & Wang, 2011). It is true that these professionals use 3D models during their individual work, yet still the collaboration remained more or less 2-D based.

A common database provided by BIM improves collaboration and communication between structural engineers and the rest of the design team (Bartley, 2017). Any change made by the other design team members is automatically tracked by the structural engineer and vice versa. Accordingly, BIM makes it possible to merge all involved disciplines into a single central digital model. (Berdeja, 2014)

#### ***2.3.1.2 Improved Visualization***

BIM enables the structural engineers to best present their design using many visualization tools. Interactive 3D models, that represent the actual real-world asset, make communication with non-technical players easier. (Bartley, 2017)

BIM workflows visualization capability is accentuated by a case study carried out by Chen & Tang. These researchers conducted a case study on a pilot project to validate the potential of BIM workflow. On their paper, they claimed that a 4D virtual simulation was created for the pilot project. Using such simulations, the professionals involved had a better understanding of the design. (Chen & Tang, 2019)

#### ***2.3.1.3 Improved time efficiency***

Hunt recognizes BIM workflow's capability in improving time efficiency (Hunt, 2013). In BIM workflow analytical and physical model are generated simultaneously. This saves the entire time that was devoted to manually creating structural model from architectural model. Additionally, the structural designer is able to integrate the analysis with preparation of construction drawing, saving more time. (Bartley, 2017)

#### ***2.3.1.4 Well Documented design process***

Additional benefit of BIM uptake is evident during documentation. All relevant information regarding the structure will be gathered and well documented in a central model. Thus, whenever information is required it can be easily accessed. Documentation of information in a common model reduces redundant re-entering of information. (Nielsen & Madsen, 2010)

#### ***2.3.1.5 Improved quality of work***

Structural design employs a trial-based work flow, where a model is continuously changed until a satisfactory result is attained. This workflow involves the continuous creation and updating of data. The need to manually handle data is reduced by employing BIM workflow (Ozturk & Eraslan, 2018). By allowing the BIM technology to handle data, errors and omissions are significantly reduced. As a result, the quality of the structural engineer's work is improved.

BIM workflow's ability to present design results in 3D model, that accurately depict the real-world condition, also improves the quality of structural engineering work (Bartley, 2017).

### **2.3.1.6 Cloud Computing**

BIM's capability can be further expanded by taking it into the internet. Using a device connected to the central database, design data can be accessed anytime and anywhere without the need to carry around drawings papers. (Bartley, 2017)

### **2.3.1.7 Better material quantities estimate**

The information rich structural models generated through BIM workflow, allow professionals to obtain most accurate material quantity estimate (Ozturk & Eraslan, 2018). Traditionally, material quantity estimate is carried out by a human and as such is prone to human error and time intense. It is true that computers are used during the work, however most of the weight is on the person. In BIM, though, the task of computing is given to computers as it should be. As a result, material quantity estimate is carried out instantaneously and with better quality than the traditional method.

### **2.3.2 Clash detection**

Conflict detection is a vital part of the design process. During design there is not a single model but rather several models integrated with each other to give a complete model of the structure. The players, during design, produce their own model which need to be overlapped to form the complete digital model of the building. (Sampaio, 2017)

One type of clash is when multiple elements occupy the same space. Sampaio, A.Z. referred to this clash as physical clashes (Sampaio, 2017). this could be, for instance, when a water supply pipe goes through a beam, a window half buried in a beam or a door with part of it buried into a column.

Another type of clash is when the space between two elements is not sufficient enough for the operation of one or more of the elements. for instance, there should be a sufficient open space at the end of a stair or at the door of a lift shaft.

Rule clashes are another category of Clashes. According to Sampaio, A.Z., these are conflicts related to elements and the associated rules they fell to met (Sampaio, 2017)

Traditionally, professionals attempt to identify clashes using 2-D drawing (Swapnesh.P.Raut & S.S.Valunjkar, 2017). Even after laboring through this task, some clashes still go unnoticed to be discovered later during construction. This results in expensive rework at construction sites. Using BIM, however, all clashes can be automatically detected during design avoiding potential conflicts during construction works. This is attributed to BIM models' high level of detail which provide a better visualization (Sampaio, 2017).

Berdeja (2014) conducted a case study to evaluate the capability of BIM with regard to clash analysis. Among the software packages used for the study was Revit 2014. The study demonstrated the capability of BIM in detecting and reconciling conflicts between design disciplines.

The author stressed that conflict detection and conciliation depend mainly on the level of detail of the project at hand which can be accomplished through BIM adoption. The researcher acknowledged that the ability of BIM to merge disciplines together was vital for the clash detection. The author believed that during clash detection, BIM usage has an undisputable advantage over traditional methods. (Berdeja, 2014)

### **2.3.3 BIM and Interoperability Issues**

The design and construction of a building is a team activity. Each team member carries out activities with the help of a software specific to that team member. Multiple software packages with overlapping data requirements are used to perform various tasks during design and construction. These tools need to exchange data amongst each other in order to adopt BIM. This ability to exchange data among software packages and for the tools to jointly contribute to the work at hand is called interoperability (Eastman, Teicholz, Sacks, & Liston, 2011).

IFC, which is an acronym for industry foundation class, is a schema developed to define an extensible set of consistent data representation of building information for exchange among architectural, engineering and construction software packages. It offers a broad, general definitions of objects and data. (Eastman, Teicholz, Sacks, & Liston, 2011)

Nielsen & Madsen (2010) carried out a study where they examined the interoperability of Revit with structural analysis tools. These tools were Robot structure, StaadPro and an add-on for Revit structure. They analyzed five structures with varying complexity.

The aim of the study was to create a bidirectional link between Revit and the structural analysis tools. The first link, that is from Revit to the structural analysis tools, worked. However, the reverse link, that is from the structural analysis tools to Revit, was found to be very troublesome and at some cases impossible. The study discussed this unfortunate situation in detail but didn't went further to provide a solution. (Nielsen & Madsen, 2010)

Xiao, Liu, Du, Yang, & Xu promised to create a bidirectional mutual conversion between Revit and a structural analysis software named PKPM. However, on their paper, they only presented half of their intention. They were able to develop a model of a high-rise shear wall structure on Revit and transfer it to PKPM for structural analysis. However, they failed to present the other direction of the link that is sending the structural analysis model back to Revit. (Xiao, Liu, Du, Yang, & Xu, 2019).

On this research, interoperability between Revit and conventional software packages (ETABS and SAFE) was discussed. A bidirectional link between Revit and the software packages was achieved through the development of tools and plugins.

## **CHAPTER 3      APPLICATION OF BIM PART I: PREPARING MODEL**

### **3.1 Introduction**

The application of BIM commences with the preparation of a central model. Ideally, the central model will serve as a common database for all the design data across multiple disciplines. For this thesis work, it will serve as a common database for structural engineering and architecture.

The central model is first prepared as an architectural model. However, as the design stage progress, the other disciplines (i.e. structural) make contribution to this model. Thus, the model will be a central model with all the design team's information.

### **3.2 Selecting BIM Package**

The task of preparing an architectural model is given for the architect. For this thesis an existing architectural model prepared using ArchiCAD and AutoCAD was used. However, the thesis couldn't proceed using those software packages.

AutoCAD performs geometric modeling not parametric modeling (which is required for BIM implementation). While it is possible to create parametric modeling in ArchiCAD, the modeling is limited to architectural objects. Revit, however, is able to create a parametric model including structural, sanitary and electrical objects in addition to architectural objects<sup>1</sup>. Therefore, the model is prepared anew using Revit so that it can be used for BIM Implementation.

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<sup>1</sup> This subject is further discussed on section 2.1.4.

The key difference between AutoCAD and Revit, according to Autodesk, is that AutoCAD is a general drawing tool with broad application while Revit is a building specific design and documentation solution. Revit recognizes phases and disciplines involved in a building project and it creates an intelligent 3D model of buildings. (Autodesk Inc., 2019)

Revit structure can create structural objects and an analytic model. However, the software does not perform structural analysis and design. Thus, a structural analysis tool is required to perform the analysis and design of the structure.

One important requirement in selecting a structural analysis tool for the thesis was the capability of the tool to integrate with the main BIM tool that is Revit. After all, a robust analysis tool that cannot be integrated with the BIM package is no use for BIM implementation.

Robot structural analysis, which is created by the creators of Revit, is a better companion to Revit than ETABS and SAFE. Nevertheless, as it is stated in the title of the thesis, the purpose of the research is adopting BIM through conventional software package (ETABS and SAFE). The reason for this decision is that BIM alters the traditional workflow immensely. As a result, it is expected to meet a resistance from design professionals. Thus, it is wise to use the software packages that are already popular with the professionals to reduce the possible resistance.

Structural designers in Ethiopia are more familiar to ETABS and SAFE than to Robot analysis. They have used those for a longer time and have developed a trust towards them. Demanding structural designers to abandon these familiar tools by a relatively new and unknown (from their perspective) tool will only create more resistance. As a result, the research used ETABS for structural analysis and design accompanied by SAFE.

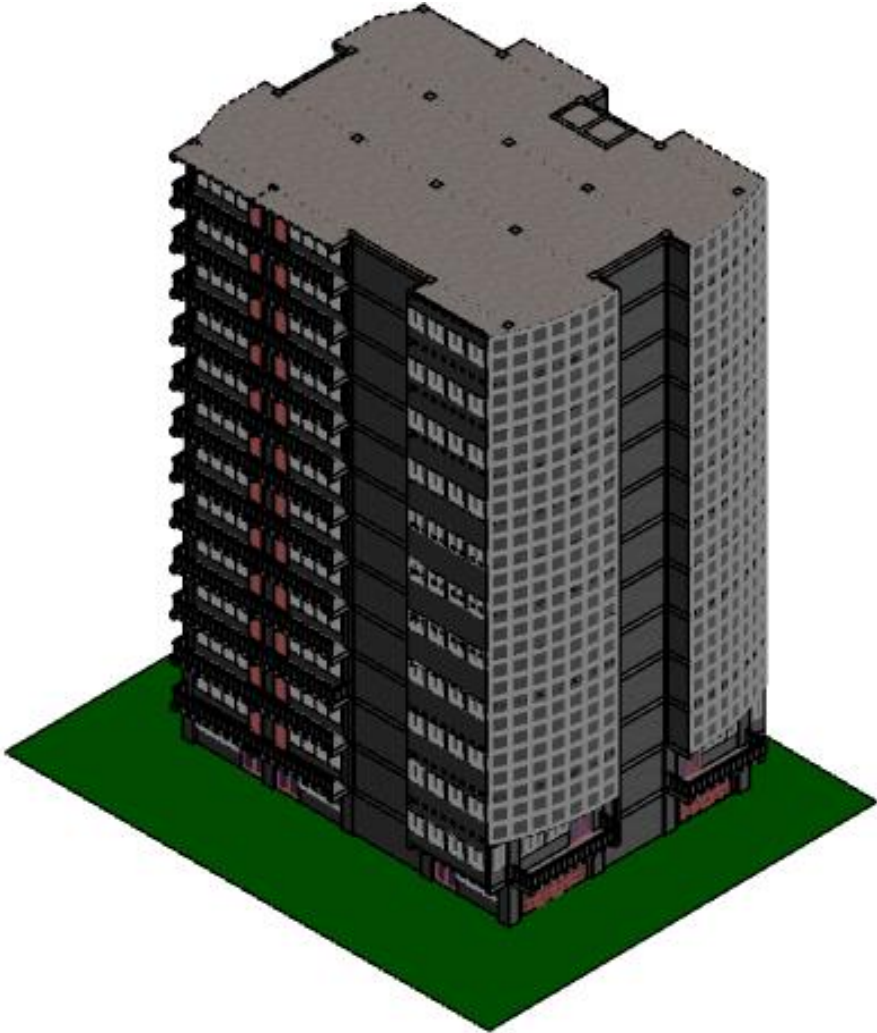
### **3.3 Creating the Analytic Model**

Traditionally, a structural engineer creates a structural model based on the architectural model. This task is essentially recreating an existing model in a different software package. This workflow wastes time and risks misrepresentation of the architect's design. On the thesis, by adopting BIM this flawed workflow is avoided.

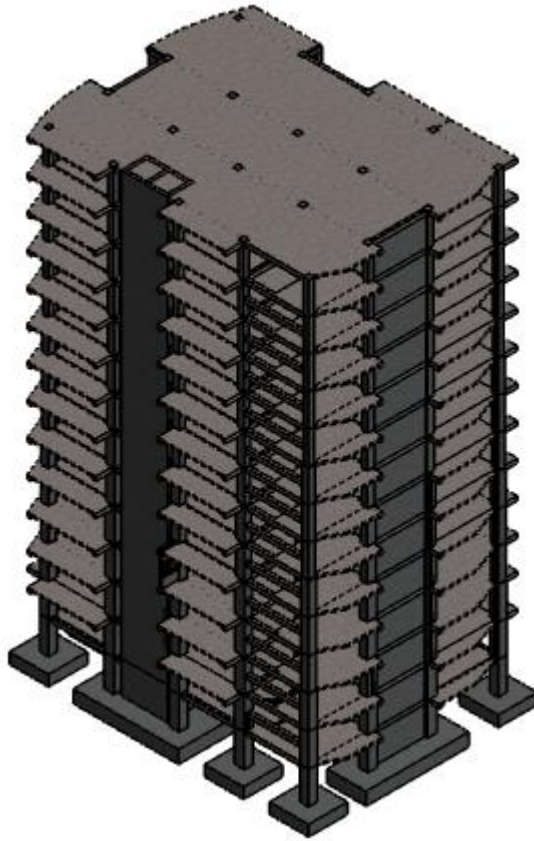
As it was evident during the research, the BIM workflow highly minimizes the modeling task of a structural engineer. In BIM workflow, when an architectural model is created, inadvertently, the corresponding structural model is also simultaneously created. Architectural components themselves (such as slabs, columns and staircase) will be used as structural components without the need to recreate.

After the architectural model containing all architectural components (along with respective structural components) was prepared, remaining structural components were added to the model. These remaining structural objects were beams, shear walls (other than the lift shaft) and foundation which were not included in the architectural model used for the thesis. Customarily, architects do not bother to create these elements during their modeling work. Thus, it is left for the structural engineer to add them.

The central model is shown on Figure 2. This model contains both architectural objects and structural objects. To aid with visualization, Figure 3 presents the model with only the structural objects displayed.



**Figure 2: Architectural model of the sample project**



**Figure 3: Central model with only the structural element visible**

### **3.4 Defining Project Information Parameters**

In Revit, “Project information” is a system family. It comes with default parameters that store project information such as address, client name, etc. However, there are no parameters that store project information required for structural analysis and design. Hence, during the research, parameters capable of storing information required for structural analysis and design were created.

#### **3.4.1 Geotechnical information**

Among the project information parameters created were a group of parameters which store information gathered during geotechnical investigating of the site. These pieces of information are useful during foundation design.

The parameters created are:

- Recommended foundation type
- Recommended foundation depth
- Allowable bearing capacity of the soil formation
- The soil formation

Some companies carrying out soil investigation may offer multiple option regarding the foundation selection. Thus, the group of parameters listed above were created twice, with one group for primary recommendations and the second group for alternate recommendations.

### **3.4.2 Structural information**

A group of parameters that store information which is required for seismic design of the project were created during the research. The parameters are:

- Structural type
- Ductility class
- Seismic zone and bedrock acceleration ratio
- Spectrum type
- Ground type
- Behavior factor,  $q$
- Importance class and factor
- Correction factor
- Regularity in elevation and plan
- Fundamental period of vibration

These parameters, along with the geotechnical parameters, were created as “Shared parameters”. In Revit, shared parameters are parameters that can be used in multiple projects. Hence, the project information parameters created for this thesis can be used in future BIM projects.

### **3.5 Defining Materials in BIM**

As in the traditional workflow, materials along with their properties were defined. However, when implementing BIM much more information can be added about a material. Three materials were defined for the sample building. One was a rebar material while the others were concrete (C20/25 & C25/30). The following are some of the information that was gathered for these materials.

#### **3.5.1 Identity**

Important descriptions can be attached to the materials. For the concrete materials detailed instructions can be specified about the preparation of the concrete. Any special care needed during preparation of the material can be recommended. For the rebar, preferred manufactures can be suggested. Website of the manufactures can be stored on the material definition.

Cost is an important factor and it was defined for the materials. This value can be used by Revit to carry out cost analysis. Any other information that is relevant to the material can be attached to it.

#### **3.5.2 Physical Property**

Physical properties of materials specified during the thesis were:

- Thermal property
- Young's Modulus, Poisson's ratio, shear modulus, density
- Compressive strength, yield strength, tensile strength

This information along with other material definitions<sup>2</sup> are stored in the central model. These physical properties can be stored in the conventional design process also. What is different here is that the properties are stored along with the identity properties of the material discussed in the previous section. This makes the information complete and integrated.

### **3.6 Structural Objects in BIM**

Structural objects including beams, columns, slabs, shear walls and foundations were part of the central model in Revit. By default, these objects are not able to store structural analysis and design information. Hence, during the thesis, these objects were made to be capable of storing large amount of structural analysis and design information either by creating them or by modifying them.

The amount of information stored in the structural elements grow as the model progressed through the design stages. For instance, at the beginning of the design stage, a beam had information regarding its size, material type and mechanical properties (Figure 4). After analysis, additional information such shear force, flexural moments and torsional moment were generated and added to the beam object (Figure 5). After design was performed, yet again more information was generated and added to the beam elements swelling the data on the beam (Figure 6). Similar process was used for the rest of the structural elements as well.

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<sup>2</sup> Information regarding the appearance of the material in the model were also specified. Even though this does not have any importance to the structural engineer, it is helpful while working with the central model.

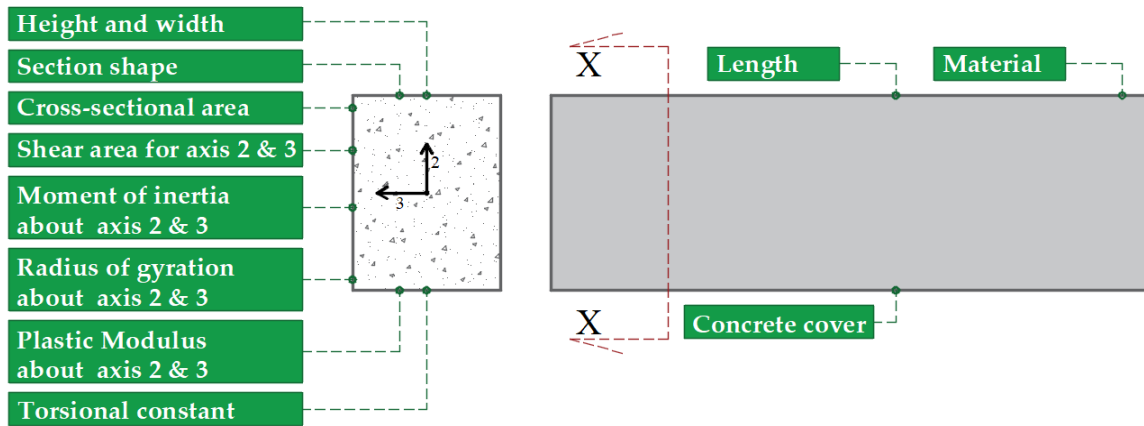


Figure 4: Data on a beam object: pre-analysis

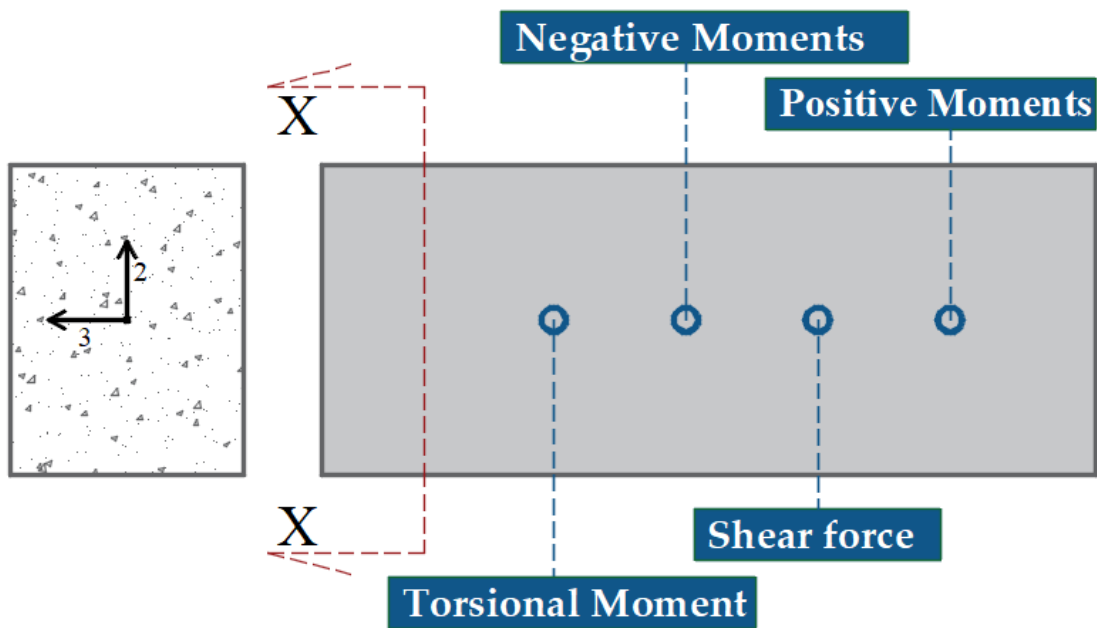
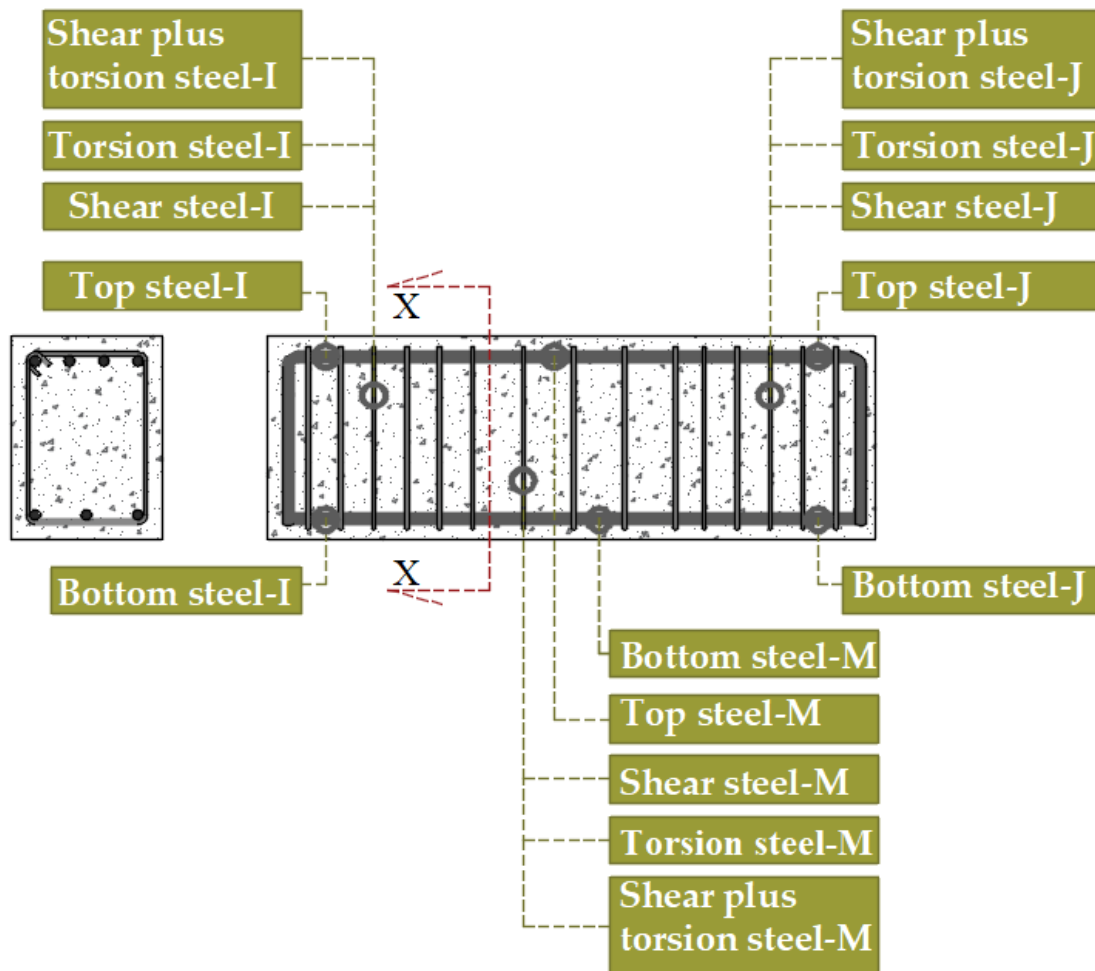


Figure 5: Additional Data on a beam object: post-analysis

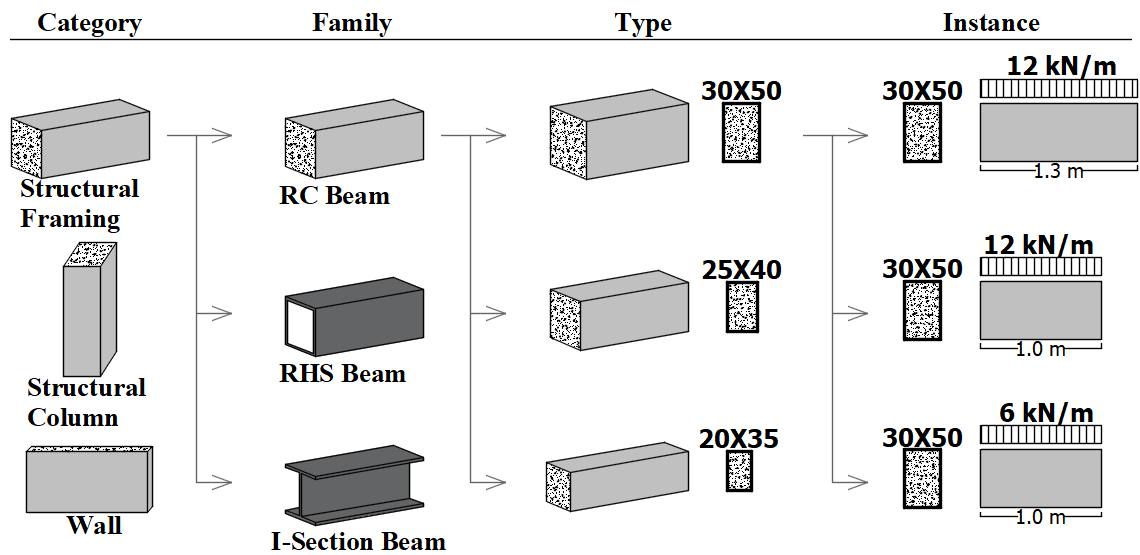


**Figure 6: Additional data on a beam object: post-design**

In Revit, it is possible to create a template element (family in Revit terminology) that can be reused by multiple projects. During this thesis, families of different structural elements that are capable of storing wide range of structural analysis and design information were created. These families were used during this research and can be used in other future BIM projects.

### **3.6.1 Data Organization and Revit Object Hierarchy**

Revit organizes objects in hierarchy. To store and organize data on the central model (on Revit), it is important to understand this object hierarchy. On the top of this hierarchy are categories followed by family, type and instance respectively. Figure 7 illustrate this hierarchy using an example. The example is furthered elaborated on subsequent paragraphs.



**Figure 7: Revit object hierarchy illustration**

Categories are pre-defined within Revit. Figure 7 presents three model categories. These are structural framing, structural column and wall.

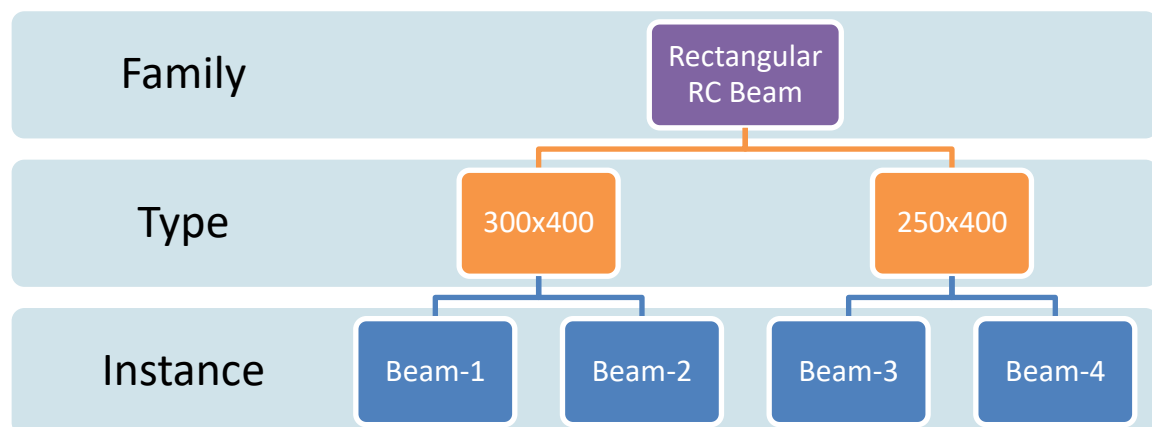
Families are a collocation of like objects sharing same general behavior and properties. On Figure 7, three Revit families are shown for structural framing category. An RC beam, RHS beam and I-section beam. Each of these families can have unlimited amount of types or family types.

Types are variations of a family. The RC beam family depicted on Figure 7 has three types. These types are differentiated based on their cross section (30x50, 25x40 & 20x35). Other means of differentiating the structural framing family can also be employed but for the thesis cross-section is used as a means to distinguish family types.

An instance is an actual physical object that is placed in the model. An RC beam (family) with cross section 30x50 (type) is placed three times in the example presented on Figure 7. The first instance of the type is 1.3-meter-long with 12 kN/m distributed load while another instance has the same distributed load but with 1-meter length. The third instance of the same type is a meter long with 6 kN/m distributed load.

The Revit hierarchy played a vital role during storing and updating of data. Figure 8 presents an example of flow of data from the top of the hierarchy (family) to the individual instances. Category is not included in this illustration since they are predetermined and not subjected to user modifications.

As presented on Figure 8, when data is attached to a family (for instance, an RC beam), it will be automatically attached to all objects in that family. Likewise, if a data is committed to a family type (for instance, 300x400 cross section), then it will be automatically committed to all the instances belonging to that particular type. None of the object belonging to the other types will be affected by this alteration. And, finally, a data placed on an instance (Beam-1) will remain on that specific instance.



**Figure 8: Example of flow of data in Revit hierarchy**

### 3.6.2 RC Beam Family

A beam family with structural analysis and design data parameters were created for the thesis. The beam objects in this beam family can store information that encompasses different aspects of the beam objects. They are equipped with parameters to accept analysis and design results. Some of the information that can be stored on this beam family are shown on Figure 4, Figure 5 and Figure 6. The complete list of the parameters created for this family is given on Table 4 of Appendix A.

Most of the data to be stored in an instance of this beam family are generated outside of Revit using ETABS. After analysis and design were completed, the results needed to be hauled back to the central model to be stored on the common database. To enable such flow of data from ETABS to Revit (known as interoperability) a tool was programmed as part of the research. The tool and its development are discussed on section 5.3.2.4.

### **3.6.3 RC Column Family**

Similar to the beam family, an RC column family was created for the thesis. The column objects in this column family also collect several pieces of information that are relevant for structural column design. Figure 9 and Figure 10 present important information that the RC column family is capable of storing. The complete list of the parameters created for this family is given on Table 5 of Appendix A.

Most of the information to be stored on the RC column family instances was generated on ETABS. After analysis and design, newly generated analysis and design data is transferred back to Revit into the column objects. A Tool was developed as part of the thesis to transfer column data from ETABS to Revit. The tool and its development are discussed on section 5.3.2.5.

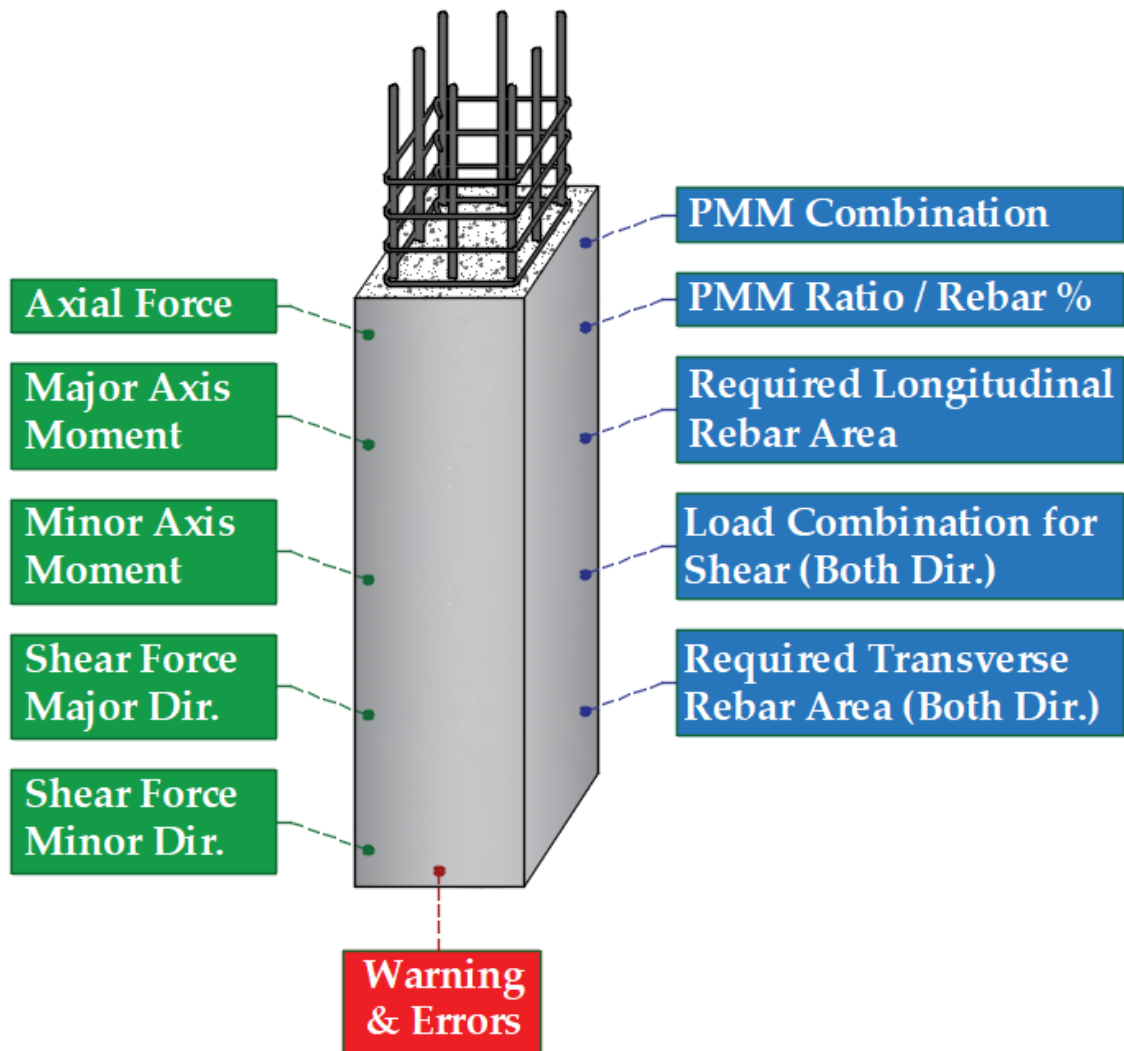


Figure 9: Some RC column family parameters

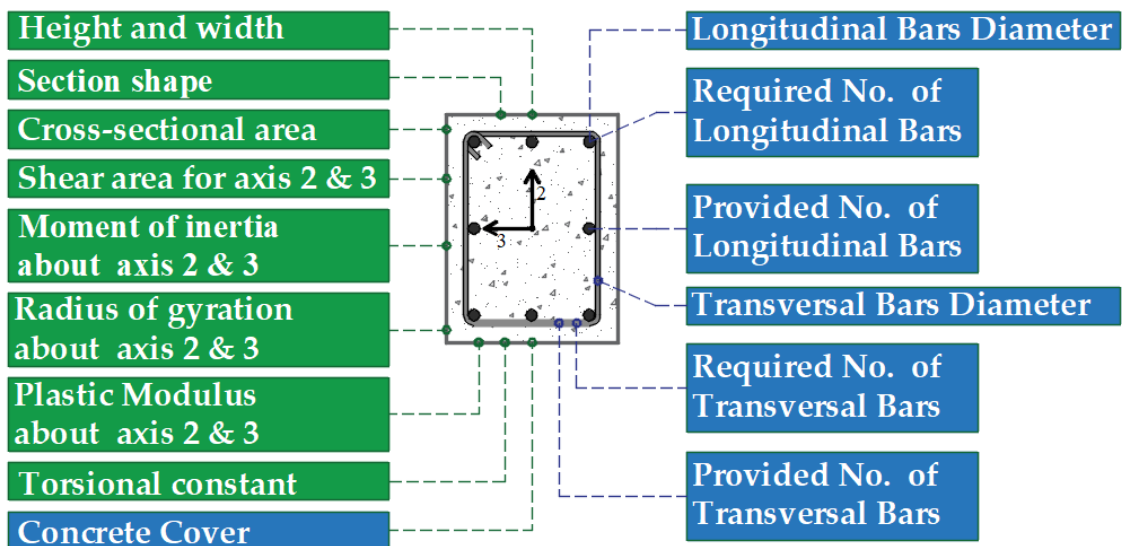


Figure 10: Additional RC column family parameters

#### **3.6.4 Structural Wall Family**

Unlike structural framing and structural columns, Revit does not allow the creation of wall family. Instead there is a wall system family. System families are built-in with Revit. They cannot be created but they can be modified.

The wall system family that is present in Revit is not capable of storing structural analysis and design data. Therefore, parameters had to be created and added to the system family to expand its capability. For the thesis, analysis and design parameters were created and added to the wall system family.

The value to be stored in these parameters are structural analysis and design data generated by ETABS. Information is extracted from ETABS and stored in the central model through a tool which was developed as a part of the thesis. The tool along with its development is discussed on section 5.3.2.3.

The structural parameters were created as shared parameters. This means any future BIM project can be done using these structural parameters. Some of the structural wall parameters are depicted on Figure 11 for pier type walls and Figure 12 for spandrel type walls. The complete list of the parameters created and added to this family is given on Table 6 of Appendix A.

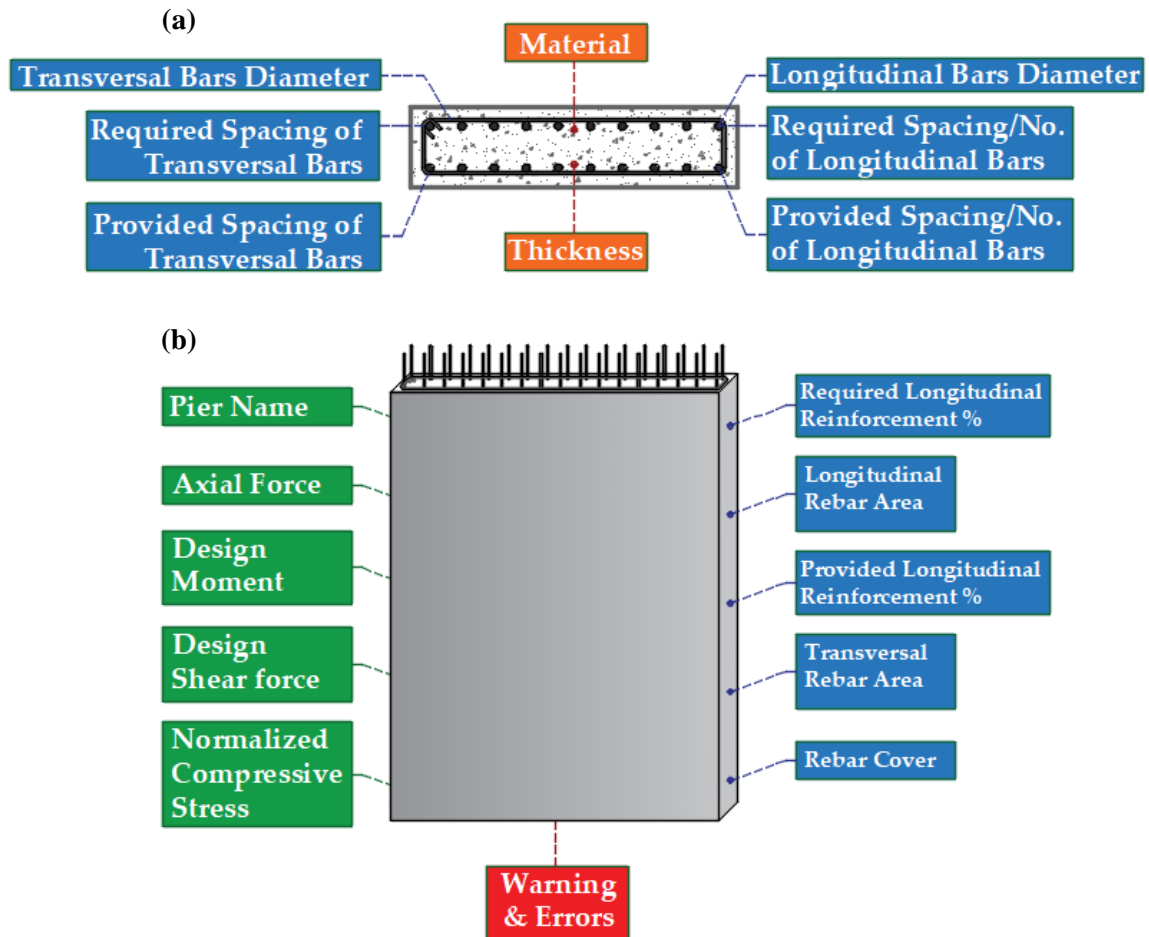


Figure 11: Some pier wall parameters (a) Section view (b) Elevation view

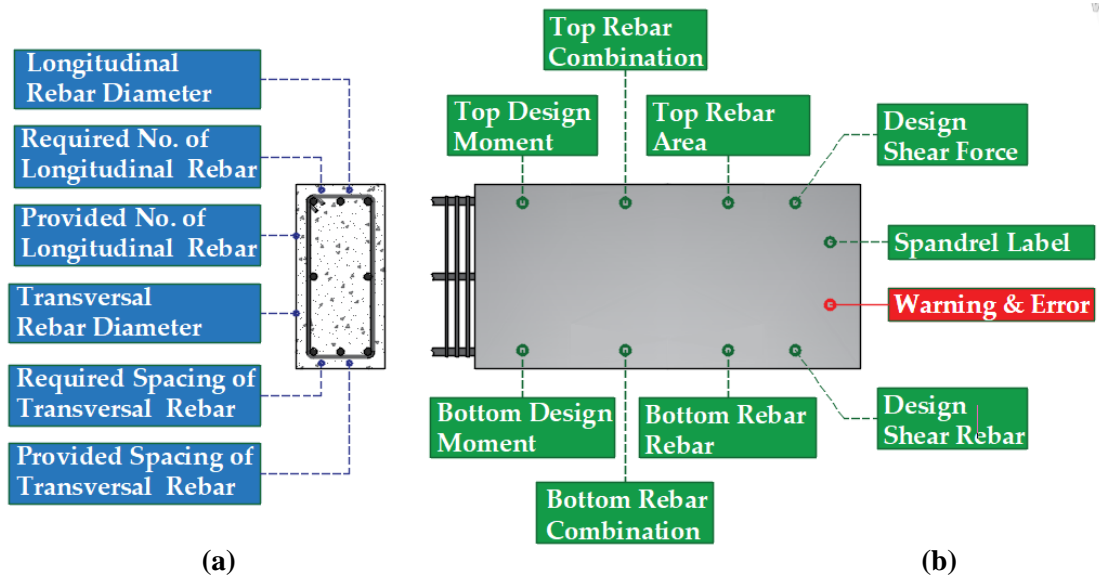


Figure 12: Some spandrel wall parameters (a) Section view (b) Elevation view

### 3.6.5 Structural Floor Family

Like structural walls, floor in Revit are also system families. They, by default, store very limited amount of data and none of it structural. To extend its storage capacity to structural analysis and design results, a number of parameters were created and added to the floor system family. These parameters are also shared parameters.

Figure 13 presents the some of the existing and newly created floor family parameters during the thesis. The complete list of the parameters created and added to this family is given on Table 7 of Appendix A. Most of these parameters are filled by values gathered from ETABS analysis result and manual inputs. A tool responsible for handling this task was created. Its features and its development are discussed on section 5.3.2.6.

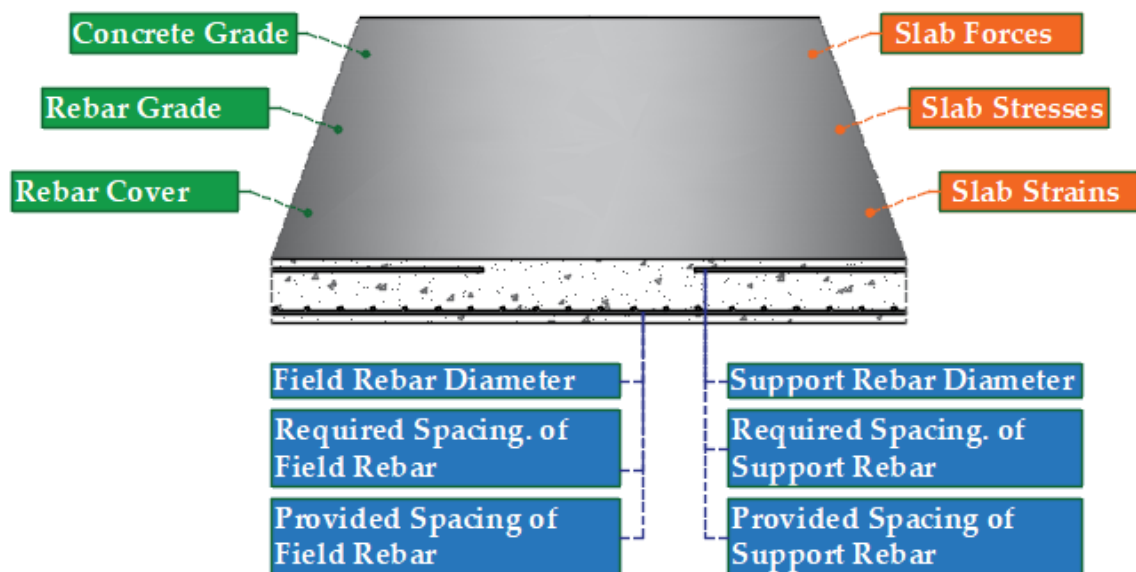


Figure 13: Some floor system family (RC slab) parameters

### 3.6.6 Foundation Families

Revit provides three families of foundations. These are isolated footing family, wall footing family and foundation slab family. The foundation slab family is a system family and hence cannot be created. The other two, however, are non-system families and thus can be created and fully customized.

Even though the non-system families are easy to work with, they cannot be transferred to SAFE for foundation analysis and design by the exchange tool<sup>3</sup>. This is an odd behavior since structural column and beam families, which are also non-system families, are handled by the exchange tool without any issue. Yet, when it comes to the foundation families, the exchange tool will only recognize the foundation system family. Consequently, all foundation objects in the model, including the isolated footings, were modeled using foundation slab system family

Large amount of foundation analysis and design data will be generated by SAFE. The foundation slab system family is not capable of storing such data. Thus, a number of foundation analysis and design result parameters were created and added to the foundation slab system family. Figure 14 and Figure 15 depicts some of the data that can be stored on the isolated footing that was created using foundation slab system family. The complete list of the parameters created and added to this family is given on Table 8 of Appendix A.

To migrate the data generated by SAFE to the central model, a tool was programmed. The tool and its development are discussed on section 5.4.

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<sup>3</sup> This tool is discussed on section 3.9

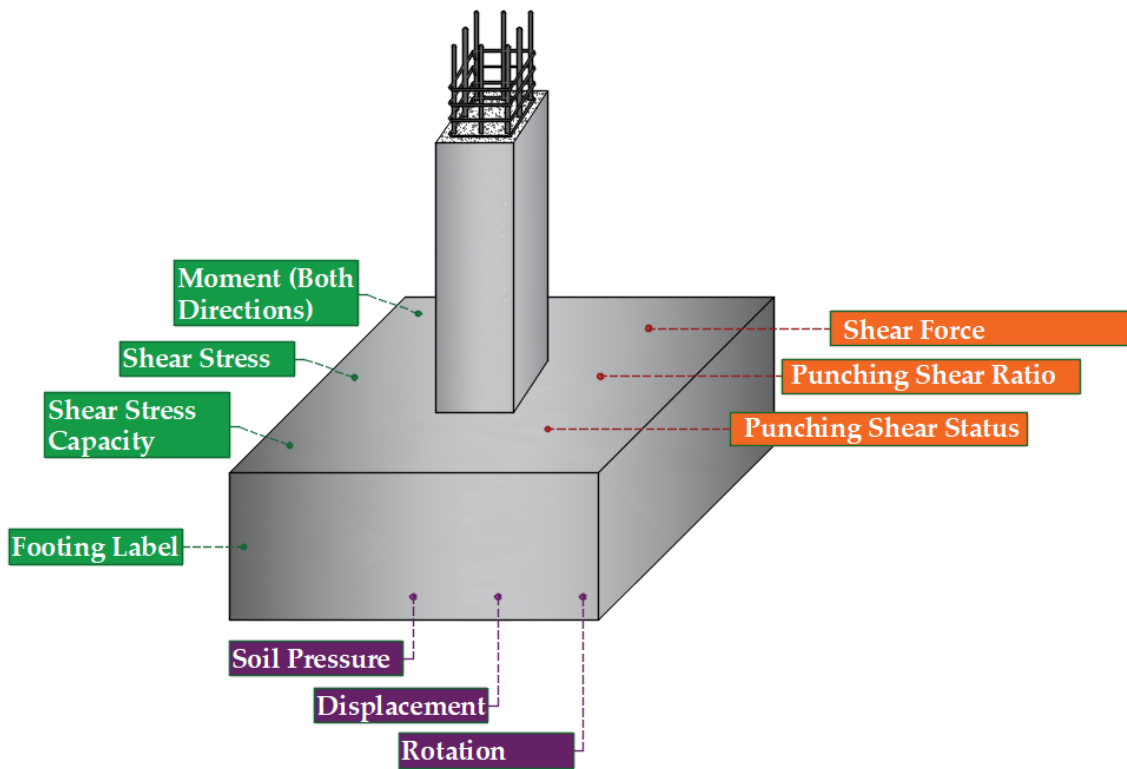


Figure 14: Foundation slab family parameters

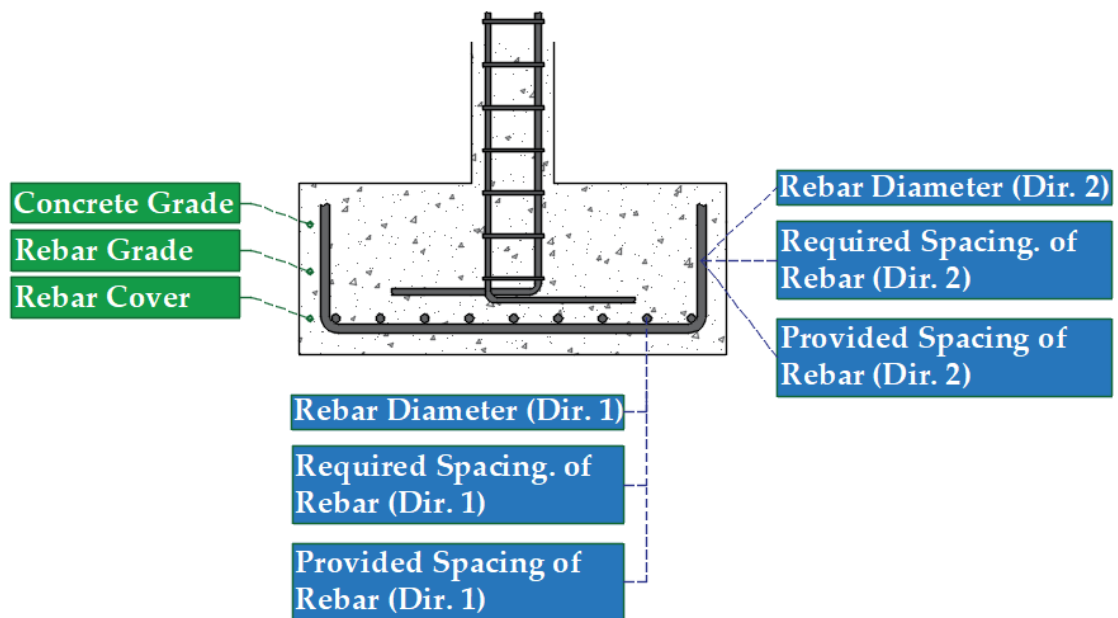
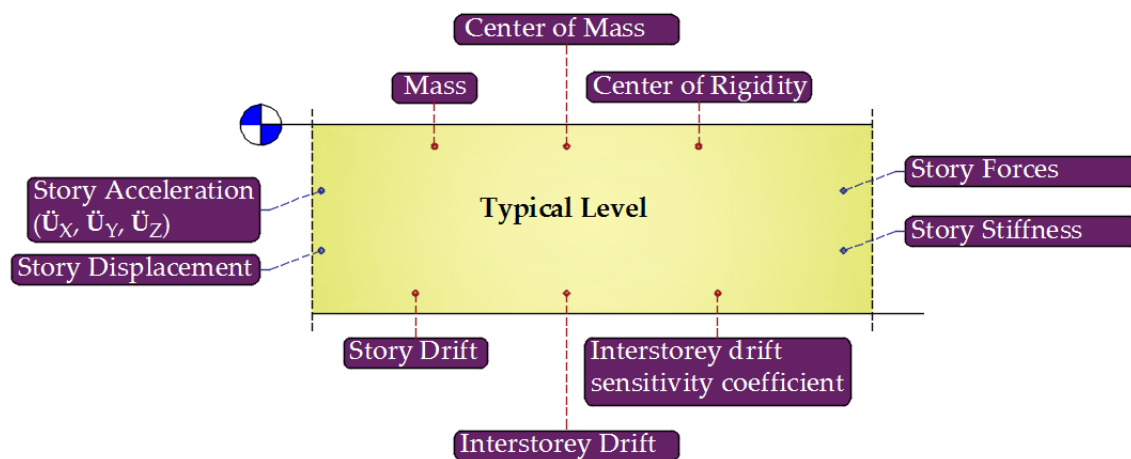


Figure 15: Further foundation slab family parameters

### 3.7 Stories in BIM

The stories (Levels, in Revit terminology) are system families. The levels under the level system family are capable of storing information regarding the identity and elevation of the level. However, they are not capable of storing any structural analysis data. Thus, for the thesis, numerous parameters representing structural analysis results were created and added to the level system family. They were created as shared parameters. Some of these added structural analysis parameters are illustrated on Figure 16. The complete list of the parameters, created and added to the level family, is given on Table 9 of Appendix A.



**Figure 16: Some level system family structural analysis parameters**

Most of the structural analysis data to be stored on the level system family were generated in ETABS. Not all of the data, however, is generated by ETABS. Some important story parameters that are not computed by ETABS are handled by a tool developed for that purpose. The tool will also send back the values it determined to the central model. Additionally, the tool extracts story data from ETABS and store them on the central model in Revit. The tool and its development are discussed on section 5.3.2.1.

### **3.8 Load case and Load combination in BIM**

Load cases and load combinations can be created in Revit or on the structural tools. Loads also can be applied on to the model in either of the platforms. However, the intent of this research is adopting BIM with minimum alteration to the conventional workflow. With that intent in mind the definition of load and the subsequent loading of structural objects were carried out on the structural tools.

When analysis is completed, the defined load cases and load combinations were transferred to the common database.

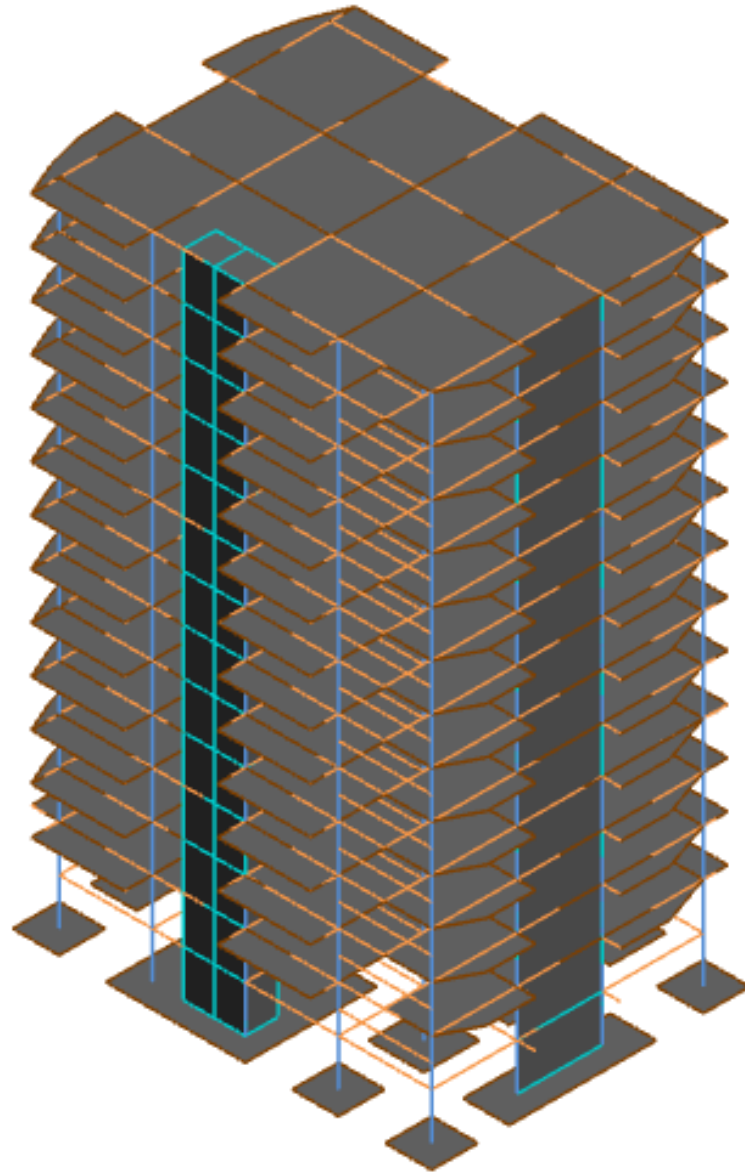
### **3.9 Exporting Model for Structural Analysis**

When the architectural model was prepared, the analytic model was simultaneously generated by Revit. However, Revit cannot perform structural analysis. For structural analysis ETABS and SAFE were chosen (See section 3.2).

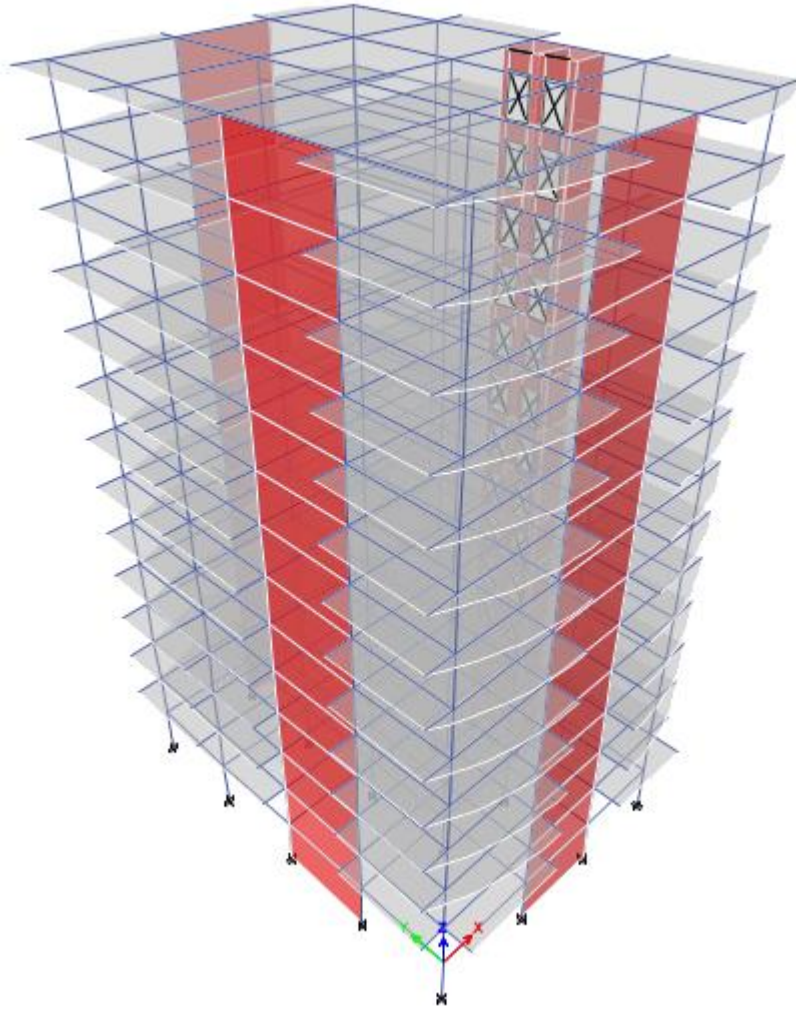
To exchange the analytic model between Revit and ETABS as well as between Revit and SAFE, a tool named CSiXRevit is used. The tool is developed by Computers and Structures, Inc. It integrates to Revit and enables exchange of information with CSI products (ETABS and SAFE) (Computers and Structures, Inc., 2018).

The scope of CSiXRevit, however, is limited. It transfers information related to grid, material property, section property and load cases and load combinations. But the vast amount of data generated during structural analysis and design is completely ignored by the tool. This creates an information island where large amount of important structural data is entirely isolated from the central model.

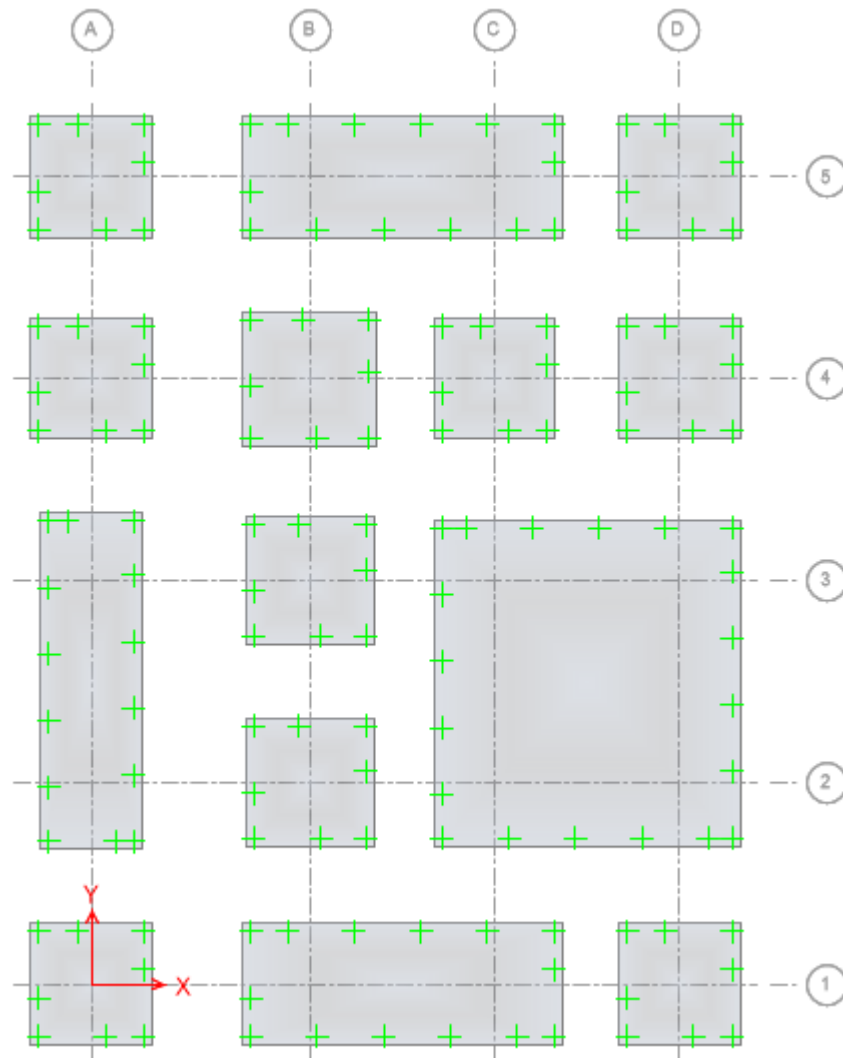
One purpose of plugin development in this thesis was to address the isolation issue discussed on the preceding paragraph. Through the tools and plugins developed, important structural information generated by ETABS, SAFE and the tool themselves was able to migrate to the central model. This assures that the common database is rich with structural information.



**Figure 17: The analytic model in Revit**



**Figure 18: The analytic model in ETABS**



**Figure 19: The foundation objects in SAFE**

Figure 17 presents the analytic model that was part of the central model in Revit. This analytic model includes all structural objects. Figure 18 presents the same analytic model but in ETABS. Here, all structural objects except for the foundations are included. The foundation objects are exported to SAFE and are shown Figure 19.

The implementation of BIM continues with the analysis and design phase of the project. The functional capability of ETABS is enhanced through the development of plugins. As a result, the need to use external application to carry out structural activities that are not covered by ETABS reduces, thereby work fragmentation is eliminated. Tools capable of migrating the large amount of structural analysis and design data from ETABS and SAFE back to the central model in Revit are also developed. These subjects are discussed on Chapter 4 and Chapter 5.

## **CHAPTER 4      APPLICATION OF BIM PART II: ANALYSIS, DESIGN AND CLASH DETECTION**

### **4.1 Introduction**

Chapter 3 concluded with the transfer of the analytic model to ETABS and SAFE for analysis and design. The current chapter picks up from that and discuss the implementation of BIM during structural analysis and design. Necessary tools and plugins were programmed as part this phase of BIM implementation.

### **4.2 Analysis Results**

For a structure to be safe and sound, there are design code mandated conditions it should satisfy. Some of the conditions govern the kind of analysis to be run while other conditions require modifications to be made to the structural model. ETABS cover some of these verifications but not all of them. However, ETABS does give the necessarily input parameters required for these verifications.

Usually, the structural engineer exports ETABS output parameters to a separate software (often MS Excel) to check analysis result against code requirements. The results of the verification remain on that separate file with no method to send them back to the model. This task fragmentation is avoided through BIM implementation. Accordingly, the verifications are done within ETABS and results are stored in the central model in Revit.

To accomplish this, first, ETABS plugins that carried out the checks and verifications were programmed. These tools are capable of exporting their result to Revit. On Revit's side, a plugin that imports the verification results was programmed; the development of these plugins is discussed in section 5.3.2 and 5.5.

On subsequent sections, some code-based checks and verifications are discussed. The verification tools that will be programmed will be based on the concept and equations mentioned in these sections.

The checks and verifications discussed are not meant to be taken as representing all code requirements. Instead, it is meant to demonstrate how structural verifications that used to be done outside of ETABS can be done, through plugins, within ETABS, further advancing BIM implementation.

#### 4.2.1 Modal Response Spectrum Analysis

According to EC8 Part 1 Section 4.3.3.2.1(1), if the building's response is significantly affected by contribution from modes of vibration higher than the fundamental mode in each principal direction, a lateral force method of analysis cannot be used. Instead modal response spectrum analysis is performed. This type of analysis shall be applied to buildings which do not satisfy the following conditions given for applying the lateral force method of analysis on EC8 Part 1 Section 4.3.3.2.1(2):

- The structure should have fundamental periods of vibration  $T_1$  in the two main directions which are smaller than the following values

$$T_1 \leq \left\{ \begin{array}{l} 4T_c \\ 2.0s \end{array} \right\} \quad (1)$$

- The structure should meet the criteria for regularity in elevation given in EC8 Part 1 Section 4.2.3.3

EC8 Part 1 Section 4.3.3.2.2(3) requires the height of the building to be below 40 meters to be able to approximate the fundamental period using EC8 Part 1 Equation 4.6.

After the analysis is completed, further verifications are carried out to check whether the analysis complies with requirement of the modal response spectrum analysis as stated by EC8. According to EC8 Part 1 Section 4.3.3.3.1(3), the response of all modes of vibration contributing significantly to the global response is considered accounted if either of the following requirements are fulfilled.

- The sum of the effective modal masses for the modes taken into account amounts to at least 90% of the total mass of the structure
- All modes with effective modal masses greater than 5% of the total mass are taken into account

A plugin to assist with modal response spectrum analysis was developed during the thesis. This plugin and its development are discussed in detailed on section 5.3.2.2.

#### 4.2.2 Inter-story Drift Sensitivity Coefficient

The value of the inter-story drift sensitivity coefficient which is computed based on EC8 Part 1 Section 4.4.2.2(2), determines whether the 2<sup>nd</sup> order effects ( $P - \Delta$  effects) should be accounted. The inter-story drift sensitivity coefficient,  $\theta$  was determined using equation (2).

$$\theta = \frac{P_{tot} \cdot d_r}{V_{tot} \cdot h} \quad (2)$$

Where

- $P_{tot}$  - The total gravity load at and above the story considered in the seismic design situation
- $d_r$  - the design inter-story drift
- $V_{tot}$  - is the total seismic story shear
- $h$  - the inter-story height.

According to EC8 Part 1 Section 4.4.2.2(2), 4.4.2.2(3) and 4.4.2.2(4), the 2<sup>nd</sup> order effects can be neglected if  $\theta \leq 0.1$ , while  $\theta$  exceeding 3 is not allowed. When the value of  $\theta$  lies between 0.1 and 0.2, the second-order effects may approximately be taken into account by multiplying the relevant seismic action effects by a factor equal to  $1 / (1 - \theta)$ .

The parameters needed to compute Inter-story drift sensitivity coefficient are made available by ETABS. A plugin was developed to compute  $\theta$ . The detail discussion of this plugin and its development are discussed on section 5.3.2.1.

#### 4.2.3 Damage Limitation Requirement

The damage limitation requirement needs to be verified in terms of the design inter-story drift ( $d_r$ ) according to EC8 Part 1 Section 4.4.3.2. The following design inter-story limits are given on EC8 Part 1 Section 4.4.3.2.

- For buildings having non-structural elements of brittle materials attached to the structure:

$$d_r v \leq 0.005h \quad (3)$$

- For buildings having ductile non-structural elements:

$$d_r v \leq 0.0075h \quad (4)$$

- For buildings having non-structural elements fixed in a way so as not to interfere with structural deformations, or without non-structural elements:

$$d_r v \leq 0.010h \quad (5)$$

These limitations can be written as follows:

$$\left. \begin{array}{l} \frac{d_r v}{h} \leq 0.005 \\ \frac{d_r v}{h} \leq 0.0075 \\ \frac{d_r v}{h} \leq 0.010 \end{array} \right\} \quad (6)$$

- $h$  - the story height.
- $v$  - the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement. It may also depend on the importance class of the building. For important class I and II,  $v = 0.5$  is recommended.

The value of  $d_r/h$  is available from ETABS. A plugin was developed to compute the parameters for each story and present the results. A detailed discussion of the plugin along with its development are discussed on section 5.3.2.1.

#### 4.2.4 Determining Structural Regularity

The structural regularity of a structure in elevation and plan influences the seismic analysis and design to be performed. According to EC8 Part 1 Section 4.2.3.1(2), the regularity of the building affects the structural model (simplified planar model or spatial model), the method of analysis (simplified response spectrum analysis or modal analysis) and the value of the behavior factor. While non-irregularity is not prohibited on EC8, it does complicate the analysis of the building.

#### 4.2.4.1 Criteria for Regularity in Plan

EC8 Part 1 Section 4.2.3.2, lists the conditions that should be satisfied to categorize a building regular in plan. The conditions are listed as follows:

- The slenderness of the building in plan shall be not higher than 4.

$$\lambda = \frac{L_{\max}}{L_{\min}} \leq 4 \quad (7)$$

- The structural eccentricity shall be smaller than 30% of the torsional radius

$$e_{ox} \leq 0.30r_x \quad (8)$$

$$e_{oy} \leq 0.30r_y \quad (9)$$

- the radius of the gyration of the floor mass in plan shall be smaller than the torsional radius.

$$r_x \geq l_s \quad (10)$$

$$r_y \geq l_s \quad (11)$$

##### 4.2.4.1.1 Computing structural eccentricity ( $e_{ox}$ & $e_{oy}$ )

As stated on EC8 Part 1 Section 4.2.3.2(6), the structural eccentricity represents the distance between the center of stiffness and the center of mass. This computation is carried out in each of the two orthogonal directions resulting in two eccentricities per floor ( $e_{ox}$  &  $e_{oy}$ ).

Center of stiffness and center of mass are determined by ETABS. Using those values, structural eccentricities can be determined manually as presented on equation (12) and (13) where  $X_{CR}$  is center of rigidity/stiffness and  $X_{CM}$  is center of mass.

$$e_{OX} = X_{CR} - X_{CM} \quad (12)$$

$$e_{OY} = Y_{CR} - Y_{CM} \quad (13)$$

#### 4.2.4.1.2 Computing torsional radius ( $r_X$ and $r_Y$ )

EC8 Part 1 Section 4.2.3.2(6) defines the torsional radius  $r_X$  as the square root of the ratio of the torsional stiffness to the lateral stiffness in the y direction. The torsional radius  $r_Y$  can be similarly determined using torsional stiffness and lateral stiffness in the x direction. Equation (14) and (15) present these computations where  $K_M$  is torsional stiffness and  $K_{FX}$  and  $K_{FY}$  are lateral stiffness in x and y direction.

$$r_X = \sqrt{\frac{K_M}{K_{FY}}} \quad (14)$$

$$r_Y = \sqrt{\frac{K_M}{K_{FX}}} \quad (15)$$

ETABS determines the lateral stiffness in both x and y direction. The torsional stiffness, however need to be calculated manually. The computation is presented on equation (16) where  $T_Z$  is torsional moment about z axis and  $R_Z$  is rotation about z axis. Both torsional moment and rotation are given by ETABS

$$K_M = \frac{T_Z}{R_Z} \quad (16)$$

#### 4.2.4.1.3 Computing radius of gyration of the floor mass in plan ( $l_s$ )

EC8 Part 1 Section 4.2.3.2(6) provides the gyration of the floor mass in plan as the square root of the ratio of the polar moment of inertia of the floor mass in plan with respect to the center of mass of the floor to the floor mass. Assuming a rectangular floor area with uniformly distributed mass,  $l_s$  can be computed as shown on equation (17) where  $l$  and  $w$  are dimensions of the building.

$$l_s = \sqrt{\frac{(l^2 + w^2)}{12}} \quad (17)$$

The input data required for making the computations detailed under this section are made available by ETABS. Yet, ETABS will not verify plan regularity. Hence, For the thesis, a tool was programmed to verify plane regularity. This tool can draw out the required data from ETABS analysis results and perform the computations needed to determine plan regularity. The tool and its development are discussed on section 5.3.2.1.

#### ***4.2.4.2 Criteria for Regularity in Elevation***

EC8 Part 1 Section 4.2.3.3 details the criteria that has to be satisfied to categorize a building regular in elevation. According to this section, all lateral resisting systems need to run uninterrupted from their foundation to the top of the building or the relevant zone. This can be verified by visually assessing the model.

The code also demands the lateral stiffness and the mass of individual stories to remain constant or reduce gradually from base to top. ETABS provides lateral stiffness and mass of stories.

If setbacks are presents, there are additional conditions to verify before categorizing a building regular in elevation. EC8 Part 1 Section 4.2.3.3(5) specifies that for gradual setbacks preserving axial symmetry, the setback of each story should not be greater than 20% of the previous floor.

For a single setback within the lower 15% of the total height of the main structural system, the setback should not be greater than 50% of the previous floor. If the setback is above 15% of the total height, the requirement changes from 50% to 20 % of the previous floor.

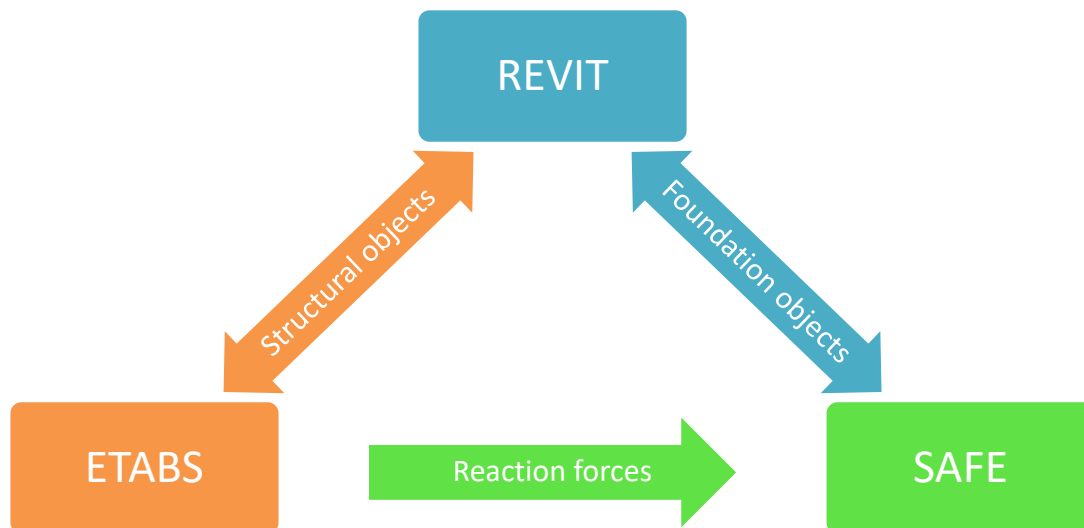
If the setback fails to preserve symmetry, two criteria are checked. The sum of the setbacks at a floor should not be greater than 30% of the plan dimension at the bottom floor. Additionally, the individual setbacks should not be greater than 10% of the previous plan dimension.

ETABS will not verify regularity in elevation. To aid with the verification, a tool was programed. This tool and its development are discussed on section 5.3.2.1. This tool is the same tool carries out previously mentioned story related computations.

### 4.3 Foundation Analysis and Design

The analysis and design of foundation objects followed, after the analysis in ETABS was concluded. Even though the task is carried out in SAFE, it requires the contribution of ETABS and Revit.

From ETABS analysis, the reaction forces at the base of the structure were determined and migrated to SAFE. From the central model in Revit, the foundation objects with their preliminary dimensions were transferred to SAFE. After foundation design is carried out in SAFE, the foundation objects with their new dimensions were send back to Revit. This interaction among the three software packages is presented on Figure 20. The exchange of objects between Revit and SAFE is similar to the exchange of objects between Revit and ETABS.



**Figure 20: Interaction of software packages for foundation design**

ETABS and SAFE have built-in capability to perform the required interaction between them. CSiXRevit handles the exchange of foundation objects between Revit and SAFE (see section 3.9). However, CSiXRevit does not handle the exchange of foundation analysis and design result data. Hence, as part of the thesis, a tool was developed to collect structural analysis and design results from SAFE and store it in the central model in Revit. The tool and its development are discussed on section 5.4.

#### **4.4 Design Results**

Design of structural objects by ETABS and SAFE concludes by providing the required steel area to resist the design forces. This information requires further treatment for it to be implemented during building construction. Bar diameter needs to be specified and respective number of bars (or spacing of bars) has to be computed.

Tools and plugins were developed for treatment of design results of structural objects. These tools retrieve design data from ETABS and SAFE and prepare a rebar set. Furthermore, similar to the analysis results, the design results need to find their way to the central model to be able to implement BIM. Since the exchange tools do not cover structural analysis and design data, tools and plugins were developed to haul the structural data from ETABS and SAFE to Revit to be stored on the central model. The tools and their development are discussed on Chapter 5.

#### **4.5 Clash Detection**

During the initial modeling, the structural objects and architectural objects were placed together harmoniously. All structural objects were given preliminary dimension and they were carefully placed so as not to clash with non-structural objects.

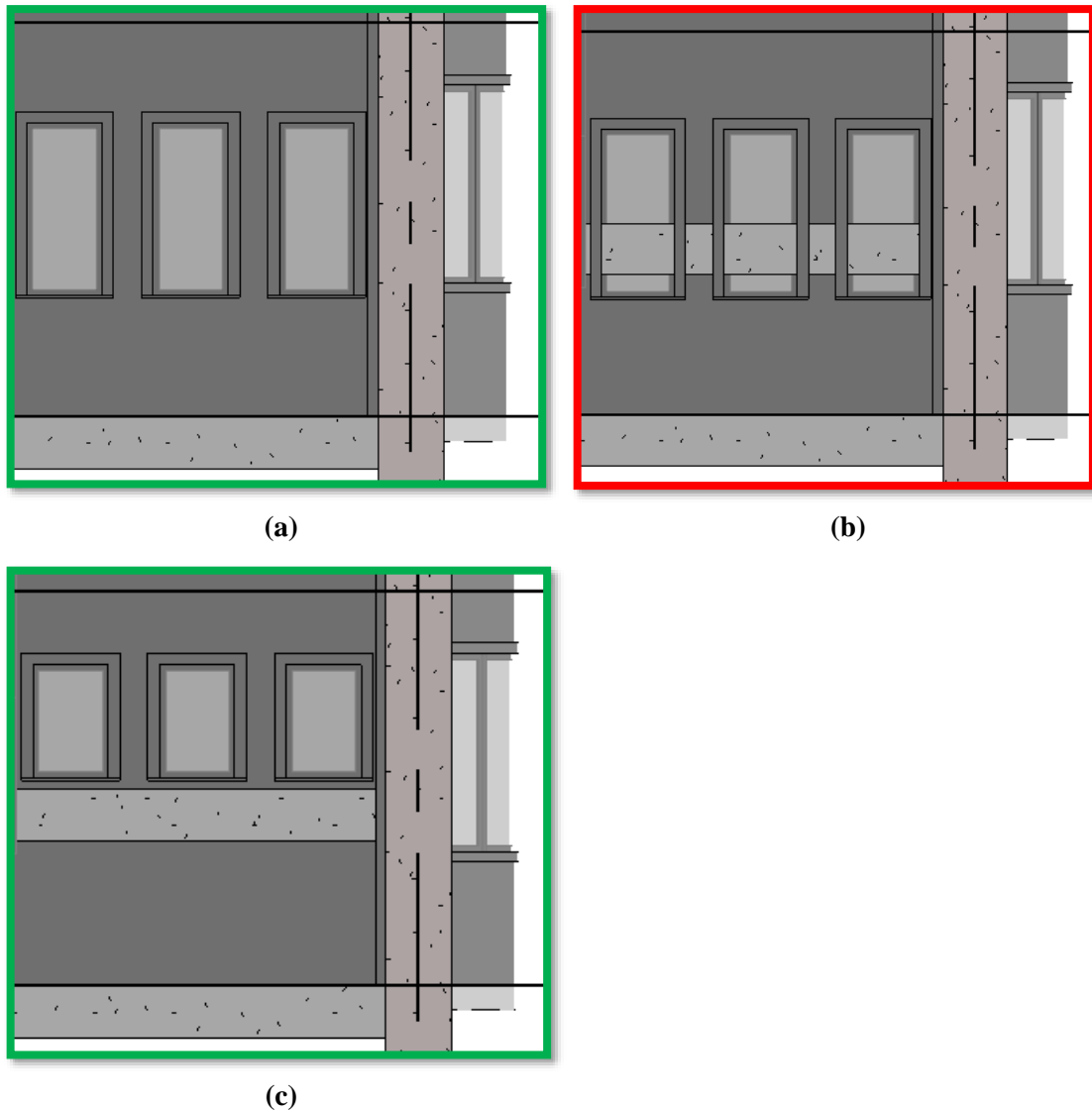
However, during analysis and design phase, the size and configuration of several structural objects were changed. Since the non-structural objects are not included in the ETABS model, their relation with the modified (and added) structural objects is unknown. Once the final model is transferred back to the central model, the impact of the design stage on the interaction of structural and non-structural objects can be assessed.

Evidently, during this research, after analysis and design were completed and the structural model was transferred back to the central model, the harmony between the structural and architectural objects were upset. Multiple non-structural objects colluded with the modified structural objects.

Traditionally, beams are not modeled as part of the architectural model. They are, instead, created by the structural engineer during the design phase. Thus, the initial placement of non-structural objects, completely disregards the existence of beams. This increases the likeliness of collusion between newly added beams and non-structural objects, specially walls, doors and windows. Such collusion did occur on the design being studied.

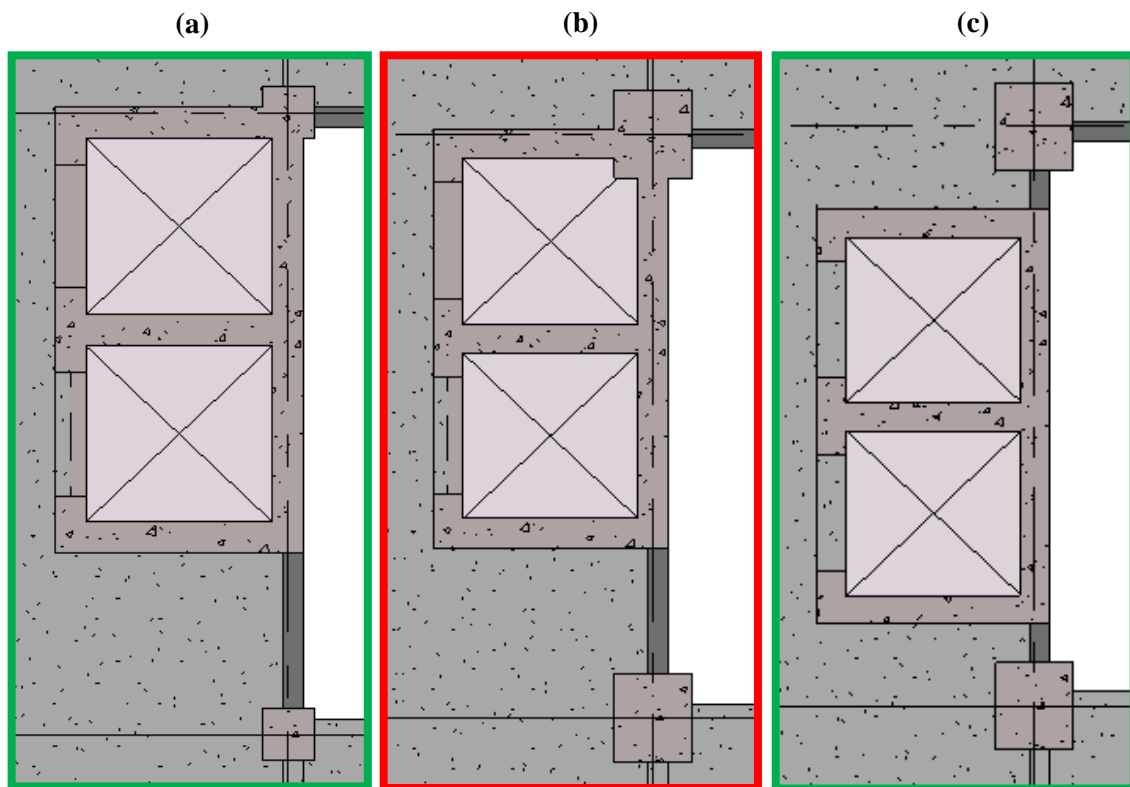
In full scope of a building design, the structural elements not only collude with architectural objects but they may also collude with sanitary and electromechanical objects. However, detecting such collusions is beyond the scope of this thesis.

During this research, the implementation of BIM workflow enabled an accurate and automated clash detection to be carried out. Unlike the conventional workflow, it comes with a built-in capability to detect collusions between objects. Most of these collusions were, but not limited to, cross discipline collusions.



**Figure 21: Beam to windows collision. (a) Initial orientation, (b) Collision after analysis and design, (c): Collision resolved**

Figure 21 presents a clash detection inaction with its solution. Initially (Figure 21(a)) landing beams for the stairs were not provided by the architect. However, when structural design was carried out, landing beams were added. And when these beams were transferred back to the central model, they collided with an existing window (Figure 21(b)). This clash was resolved by resizing the three windows (Figure 21(c)). This resolution is one solution used during the thesis. In the real-world, other solution can also be provided by discussing it with the architect.



**Figure 22: Lift shaft to column collision. (a) Initial orientation, (b) Collision after design, (c) Collision resolved**

Figure 22 presents a collision that occurred between a lift shaft wall and adjacent columns. During initial configuration (Figure 22(a)), the lift shaft was placed with its interior face aligned with an adjacent column's exterior face. The column size was 500X500 mm. Similar size and orientation was used for all the floors.

After design, the size of the columns adjacent to the lift shaft changed. For instance, on the first floor the column was increased to 900x800. With this new size, the column expands into the lift shaft, obstructing the lift car's passage way (Figure 22(b)). To resolve this, the lift shaft was moved so that it rest exactly between the two adjacent columns (Figure 22(c)).

Similar to the clash presented on Figure 21 and Figure 22, many other clashes were tracked and resolved. The summary of these collisions along with the number of times they occurred for the project considered in this thesis is given on Table 2. These collisions are between structural objects and architectural object on the exterior face of the model. The architect and structural engineer are responsible for these objects. Thus, the two parties shall normally resolve the collision in consensus.

**Table 2: Detected clashes between building objects**

<b>Colluding objects</b>	<b>Number of occurrences</b>
Landing beam and windows	13
Floor beams with windows	3
Columns with doors	16
Columns with hand rails	12
Columns with lift shaft	10

The clash detection run at this phase of a building project has two major benefits. The first is preemptively dealing with the collisions so that they won't pose problems during construction phase which will be expensive. The other benefit is accurate quantity and cost estimation. Overlapping objects, if not identified, will lead to double counting where objects covering the same space are counted. This causes inaccurate quantity and cost estimation. Hence tracking and resolving such overlapping is necessary.

#### **4.6 Preparing Construction Drawing**

So far, through the developed tools and plugin, vast amount of data has been transferred from ETABS to the central model. At the current stage, the central model (common database) stands rich in structural analysis and design data. All conflicts among structural objects and non-structural objects has been resolved. The remaining task is preparing the construction drawing.

The construction drawing for the sample project was prepared in Revit on the central model. The advantage of preparing construction drawing through BIM workflow over the conventional method were evident in both preparing the drawings and in reading them.

Usually, preparing construction drawings involve drawing the structural objects followed by adding their reinforcements. The first part of the task is basically recreating the structural objects, that were on the design tool, on a drawing tool. No new information is created here. By adopting BIM, however, this part of the task is entirely avoided. None of the structural object were required to be created since they already exist on the central model. Hence, the construction drawing preparation only required adding reinforcement bar.

The intelligence of the BIM package was evident while adding reinforcements. Conventional CAD packages recognize reinforcements only as geometries. On the contrary, BIM packages understand what reinforcements are (see section 2.1.3). Rebar diameter, spacing or number of bars and rebar cover are all understood by BIM packages.

On the central model, rebar cover values were assigned to all structural objects. Revit recognizes these values and makes sure all rebar are placed with the specified rebar cover. Revit also recognize that bars may be placed based on number or spacing and provides these options. Both these options were used during construction drawing preparation.

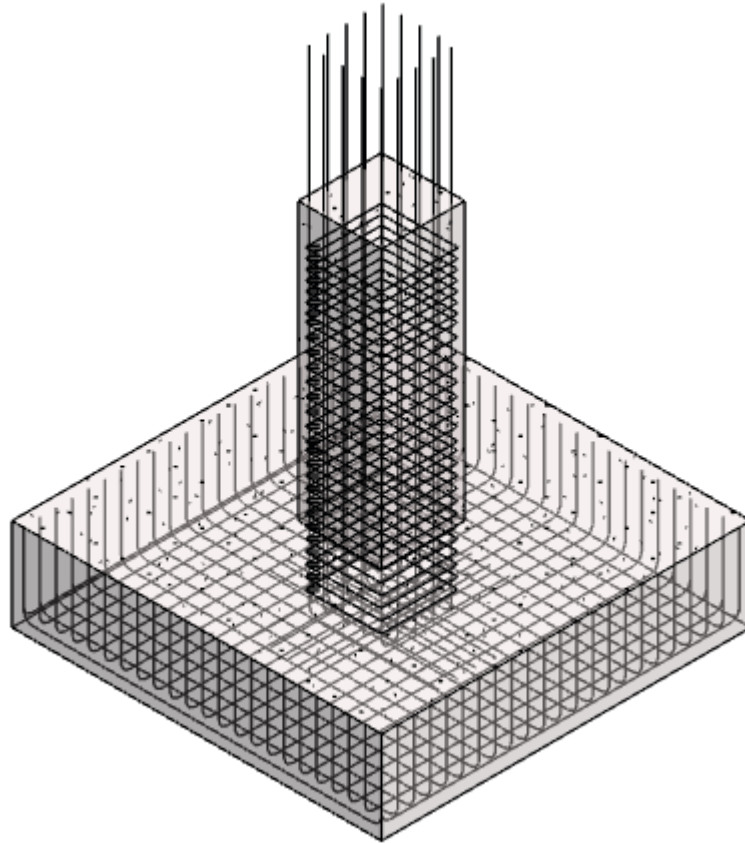
The rebar set for all structural objects on the ETABS model has been previously determined using plugins developed for this thesis. Since these plugins sent all their information to the central model, all the structural objects in Revit contain reinforcement information. Thus, there were no need to refer to the ETABS model while preparing the construction drawing.

In the conventional workflow, to fully illustration the rebar set of an object, multiple drawings of that objects from different views needed to be prepared. While this uncovers new information it also includes redrawing of existing objects. Furthermore, even though such drawings represent the same rebar set, they are not connected with each other. This may lead to inconsistencies. Both these issues are resolved by the BIM workflow.

BIM technology is capable of generating multiple views of an object. Therefore, during the thesis, multiple drawings of an object weren't manually prepared. Instead, once the rebar set of an object was drawn, it was possible to automatically generate several views, eliminating the rework mentioned on the above paragraph. Furthermore, since these multiple views were integrated with each other, there was no risk of inconsistencies.

On the preceding paragraphs, the advantages of BIM workflow while preparing the construction drawing was discussed. The BIM workflow has benefits when it comes to reading the construction drawing as well. The construction drawing was prepared in 3D making it easier to visualize. It digitally represents what the actual bar setup would look like in the real-world.

Figure 23 presents an isolated footing found in the sample project and its reinforcement. It was isolated from the entire 3D model for a closer look. To further understand the rebar set, a more closer look can be taken. The bar diameter and spacing information is attached to the bars and can be seen at any time. A tag displaying such information can easily be generated. Overall, the BIM technology provides a powerful visual capability.



**Figure 23: 3D view of isolated footing reinforcement**

Another benefit of preparing the construction drawing using BIM is improved communication and cooperation. Communication through 3D structural model, with both technical and non-technical players, is much easier than through 2-D drawings. Professionals at construction site can execute the structural designer's intent more accurately by using the 3D structural model.

Further benefits of BIM can be attained during quantity and cost estimation. These tasks are automatically done by the BIM package and thus provide accurate results. However, that subject is beyond the scope of this thesis and therefore not discussed any further.

The BIM workflow employed during this thesis concludes with the preparation of the 3D construction drawing. On the next chapter, the tools and plugins developed for the workflow are discussed in detail.

## CHAPTER 5 INTEROPERABILITY AND DEVELOPMENT OF TOOLS & PLUGINS

### 5.1 Development of Tools and Plugins

An application can be programmed as a standalone client (applications) or as a plugin<sup>4</sup> in a host program. However, not all software packages have these capabilities. ETABS can be accessed from external clients and plugins while Revit can only run plugins in-process. SAFE, on the other hand, give access to neither external applications nor in-process plugins.

A software's readiness to be accessed by external application affects the programmer developing the application. During coding, a programmer needs to see how the codes are executed and check whether they are functioning as intended. The programmer achieves this by debugging<sup>5</sup> the written code. This action was performed repeatedly throughout the coding of the plugins developed for this research. Every time a block of code was written, it was followed by a debugging. In total, thousands of lines of code were written during this thesis and debugged hundreds of time. Evidently, debugging was one of the main parts of the programming phase.

When a block of code is debugged, the code is compiled and the application is run. If the application is a standalone client, it is run with ease. However, if the application being programmed is a plugin to a host program, then the host program needs to be opened anew for the application to be debugged. This is not a dire problem but it is an inconvenient one. This fact played a significant role during the programming phase of this thesis. This will be discussed on section 5.5.

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<sup>4</sup> A plugin (or plug-in, add-on) is a software that is installed on a program to add specific features and capabilities.

<sup>5</sup> Debugging is the process of locating defects within a computer program and amending them.

The development of all the tools and plugins is geared towards smooth implementation of BIM. The tools developed for Revit function smoothly with their ETABS counterparts. These tools shouldn't be seen as performing different tasks. Instead, they are performing different parts of a single task. Since it was evident that developing tools for ETABS is much easier, most part of the task is performed by ETABS.

## 5.2 Bridging ETABS and Revit

All the objects in Revit and ETABS have a unique id to identify them with. This id is automatically generated by the software platforms and can be changed by users. The unique id of a certain object in Revit (the central model) is identical with the id of that same object in ETABS. Whatever modifications the object went through; its unique id remains unchanged.

Another unique object identifier used both in ETABS and Revit is GUID<sup>6</sup>. This identification is automatically generated by the software packages and it cannot be changed. This makes it less flexible and more secure than unique id. All objects in both platforms have a unique GUID. Like unique id, GUID also remain unchanged regardless of the changes the object goes through. However, unlike unique id, GUID of objects changes when they are moved from one platform to another (ETABS to Revit and vice versa). Consequently, GUID cannot be used to establish a bridge between the two-software platform. As a result, in the thesis, unique ids are exclusively used as a link between ETABS and Revit as well as between SAFE and Revit.

Stories are not considered as object in ETABS and as a result, they do not have unique ids. Their Revit counterparts, Levels, have unique ids. Yet, its absence on ETABS means that it cannot be used as a link between the two-software package. Their label, however, unless changed by users, is identical in both platforms. Thus, their label was used as a base for linking the stories across the software packages.

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<sup>6</sup> GUID stands for Globally Unique Identifier.

### **5.2.1 SBIM File Type**

An SBIM file type (\*.SBIM) was created to be used as a means of communication between ETABS plugins and Revit plugin as well as SAFE plugin and Revit plugin. When an ETABS plugin saves or exports data, an SBIM file is created. Later, the Revit plugin will read this SBIM file, unload its content and load it onto the central model.

The first line of the SBIM file states the ETABS plugin's name. This line later will be used by the Revit plugin to identify its content. After the first line, the ETABS plugins will save their output data in an organized form. If the particular plugin saves multiple categories of data, it will add a category identifier label before each category of data is saved. This organization is recognized by the Revit plugin.

When all opening, saving and exporting of data is carried out by the tools, a filter that filters \*.SBIM file types is applied. Thus, file exploration is much easier.

### **5.3 Developing ETABS Tools for BIM Implementation**

Unlike Revit, ETABS can be accessed from an external application. This means, tools can be developed as an external application that are capable of doing everything a plugin does. ETABS need to be open for the application to access it. However, since the application is not part of ETABS, it can be opened independently.

Developing the ETABS tools either as an external application or a plugin has merits and drawback. When the tools are plugins, they have a better integration with an open ETABS model. The drawback to this option is that ETABS need to be always open to do any task. If the tools are external, however, they can be used with ETABS tables even if ETABS is not opened.

Fortunately, the development of ETABS plugins and external tools is, for most part, identical. During this thesis, all the ETABS tools were coded as an external tool up-to their completion<sup>7</sup>. After the tools are finalized, they are duplicated and the copy is modified to be a plugin.

Lists of important codes form the source code of the ETABS tools are given on Appendix B Table 10 and Table 11.

### **5.3.1 ETABS Tool Development Workflow**

The internal process of the programmed ETABS tools has some similarities. Figure 24 presents the general flowchart of the tools. Through section 5.3.1.1 up to 5.3.1.7 each steps of the flowchart are discussed.

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<sup>7</sup> This is because debugging a standalone application is much easier than debugging a plugin within ETABS.

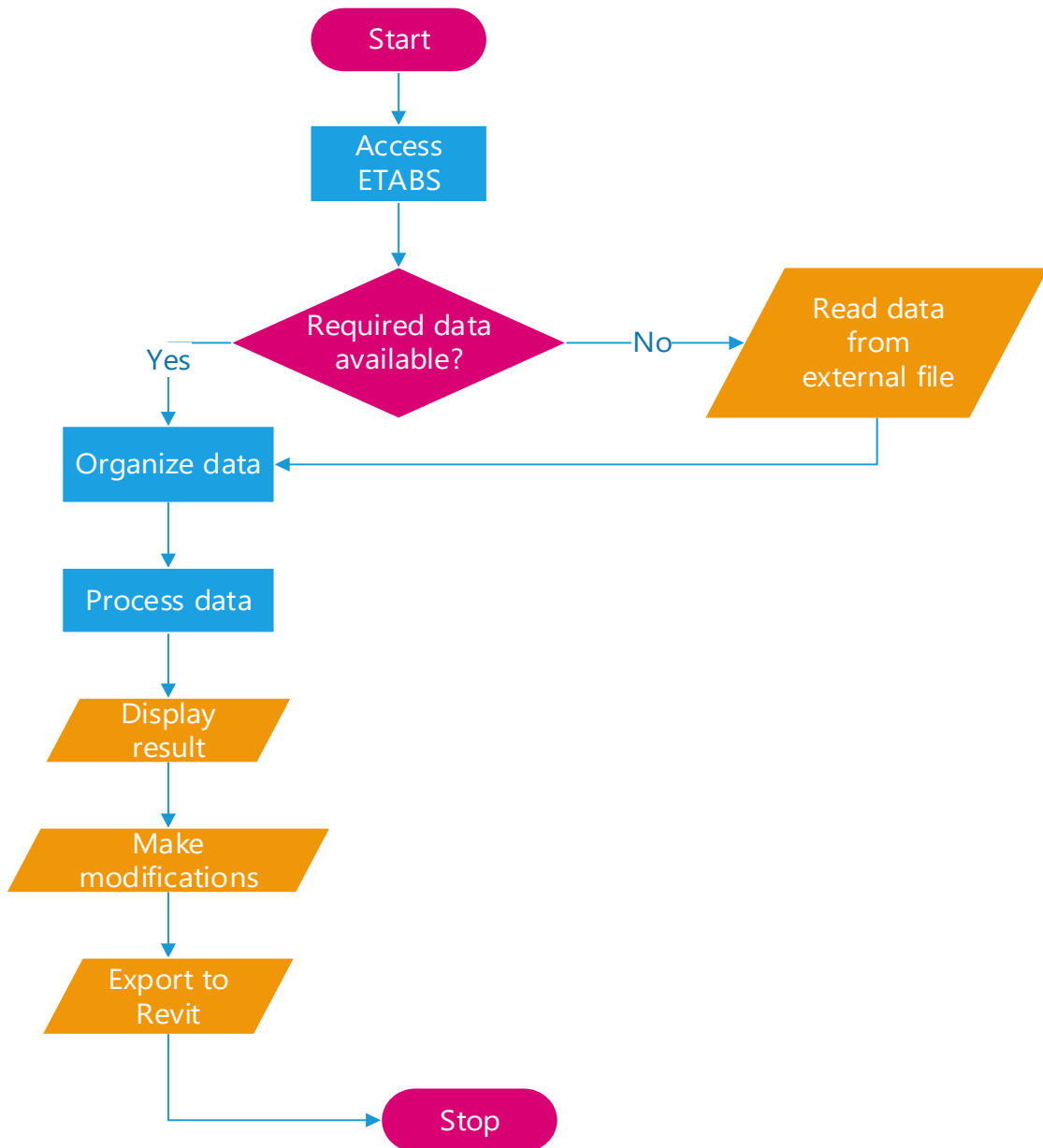


Figure 24: ETABS tool's general flowchart

#### 5.3.1.1 Access ETABS

This block of codes attempts to get access to ETABS's API. If the tool is a plugin, the attempt is almost always successful. If the tool is an external application and ETABS is not opened, the attempt fails. Nonetheless, the application continues to function.

#### 5.3.1.2 Checking available data

The required ETABS data for the required by the tools is either pulled from an open ETABS model or accessed from ETABS output tables.

#### 5.3.1.2.1 From an Open ETABS Model

This option utilizes the ETABS API to access the current open model and most of the information stored in it.

**Merit:** Since the API gets data directly from an open model, the data gathered is up to date. Furthermore, it avoids the need to export ETABS data to tables.

**Demerit:** Every time the API is used the ETABS model must be open. To get analysis result, the analysis must be run and the same goes for design results. Furthermore, not all analysis and design information stored in the model are exposed through the API. When this is the case, ETABS tables are used.

#### 5.3.1.2.2 From ETABS tables

ETABS can produce analysis and design results in both MS Excel and MS Access file<sup>8</sup>. And both of these can be accessed using their respective API.

**Merit:** Compared to ETABS's API, much more data is available through output tables. Once these tables are exported to MS Excel or MS Access, the ETABS model is not required to be open.

**Demerits:** The output tables need to be updated every time as the ETABS file is changed. It is true that this is done through few mouse clicks, however, since an external software package is involved in the process, it adds an extra step to the process.

Both of the options mentioned above are used throughout the application development. Since using the open ETABS model as a data source is more advantageous, it is used as the default option whenever possible.

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<sup>8</sup> ETABS can be setup to automatically save multiple selected tables in a single MS Access file. This automated option is much better than manually exporting each ETABS tables as MS Excel file.

### **5.3.1.3 Organize data**

Most of the data generated and made available by ETABS is provided as a set. The programmer requesting a data set do not have a say in the content of the dataset. All the programmer can do is filter it and organize it into a desirable format.

For instance, the command “GetAllFrames” retrieves data for all frame objects in the model (beam and column). The retrieved data for each frame includes, name, section name, story name, name of both end points, the x, y, z coordinate for both end points of a frame object. The programmer can then filter (separate the beams from the columns) and organize the data by story.

### **5.3.1.4 Process data**

This part of the flowchart is unique for each particular tool. This is where the computations are done. The input for this phase is different for each tool and the same is true for its output.

### **5.3.1.5 Display result**

The ETABS tools present the result from their computation in tables.

### **5.3.1.6 Make modifications**

Some of the tools provide result for observation. Based on the observation, changes may be made to the ETABS model. Other tools, provide the opportunities for modification of the result itself. These tools are the one related to reinforcement where the user can alter rebar sets.

### **5.3.1.7 Export to Revit**

The main goal of this entire endeavor is BIM implementation. That means this is a very vital last step. Here all the data that was generated by ETABS and later organized and processed by the particular tool is exported into a file (SBIM file<sup>9</sup>) that will be imported into the Revit model.

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<sup>9</sup> See section 5.2.1

### 5.3.2 The ETABS Tools

#### 5.3.2.1 Story Data Manager tool

This tool will extract, organize, process and export data related to each story. The following are list of story parameters that are either extracted from ETABS or computed by the tool using raw ETABS data.

- Story forces,
- Maximum and average story displacements,
- Maximum and average story drifts,
- Inter-story drift sensitivity coefficients and related remarks
- Damage limitation coefficients and remarks,
- Story stiffness,
- Center of mass and rigidity
- Center of mass displacements
- Story acceleration
- Story slenderness
- Structural eccentricity
- Torsional radius
- Radius of gyration of story mass
- Regularity in plan
- Regularity in elevation

Most of the story data generated by ETABS cannot be accessed using API. Consequently, these data are extracted from output tables. The tool is capable of extracting the required data from either MS Access or MS Excel. MS Access is given priority since it provides multiple categories of output in a single file as opposed to MS Excel which uses separate file for each category.

Some adjustments were applied to the tool and ETABS to make the process more automated. ETABS was setup to automatically save selected tables to MS Access every time analysis is run. The tool was programmed to attempt to automatically access these database contents at runtime, make computation and present results. Based on these setups, every time analysis is run, story data tables will be updated. And every time the tool run, it will automatically perform all its activity.

The tool's carries out five tasks. It extracts the structural analysis data generated for the stories by ETABS (Figure 31), computes inter-story drift sensitivity coefficients and damage limitation parameters for each story (Figure 32) and verifies whether the requirements for regularity in plan and elevation has been met (Figure 33 & Figure 34). The flow charts of each of these tasks are presented on Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29 respectively.

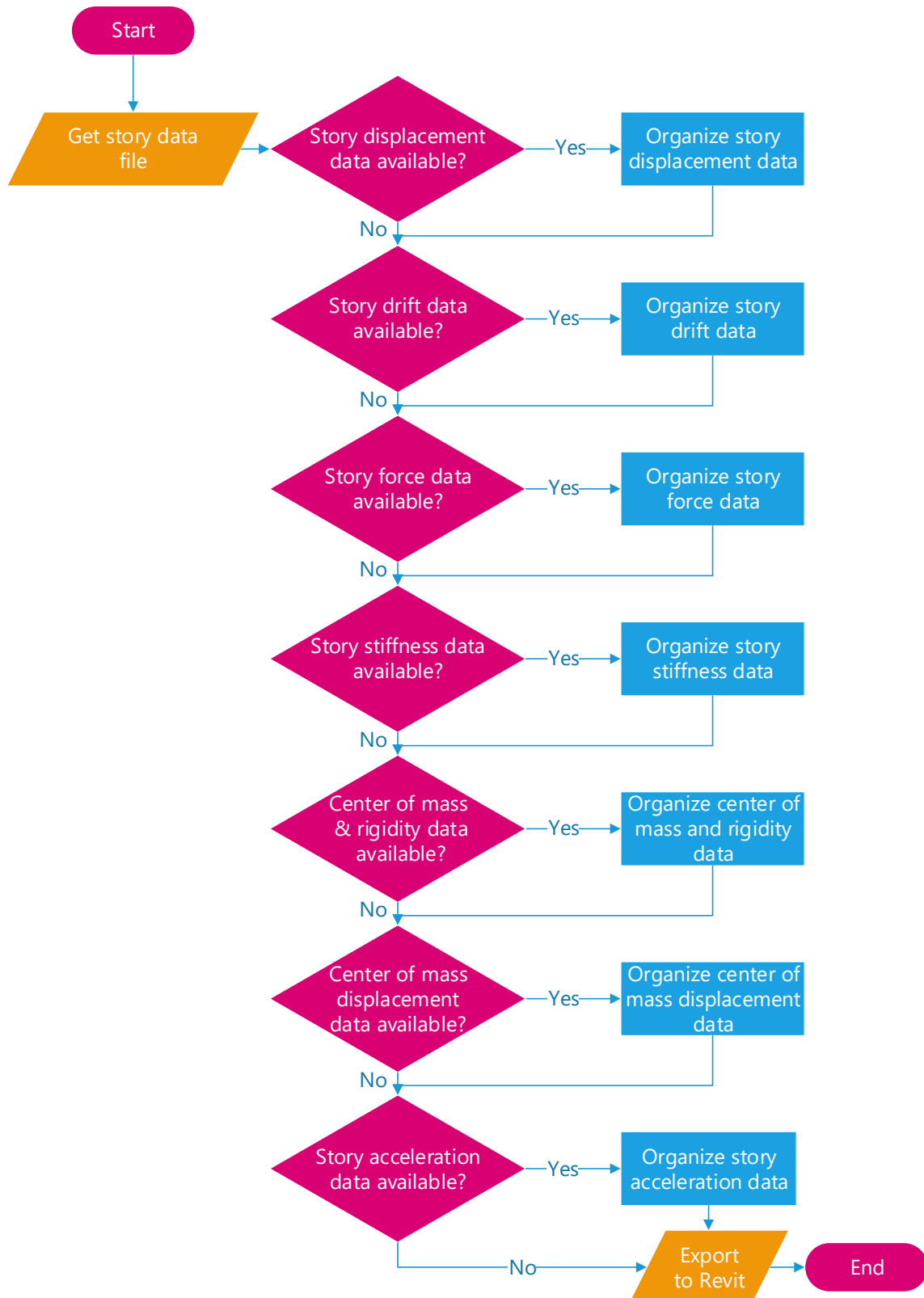


Figure 25: Story data extraction flowchart

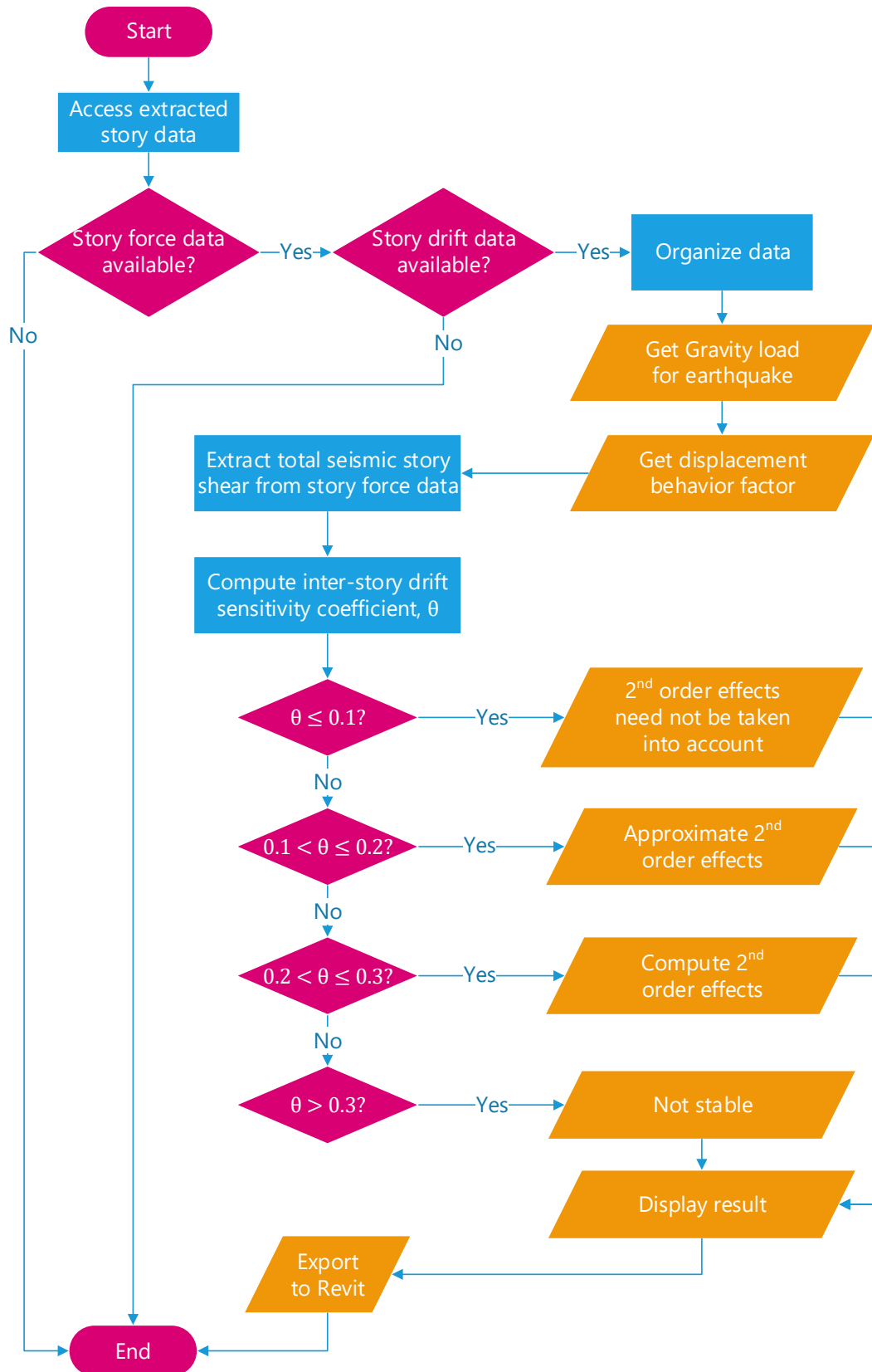


Figure 26 Inter-story drift sensitivity coefficient computation flowchart

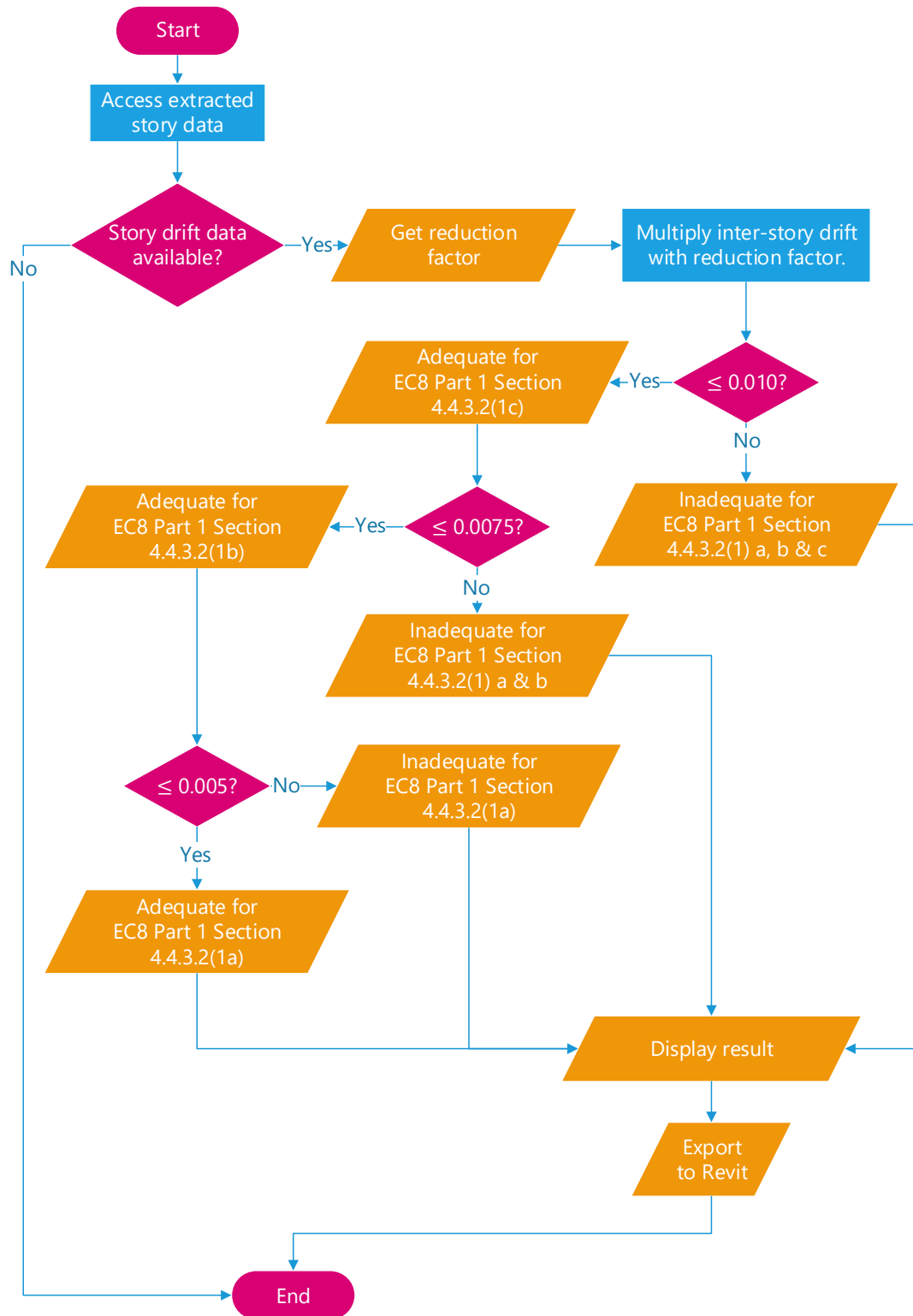


Figure 27: Damage limitation verification flowchart

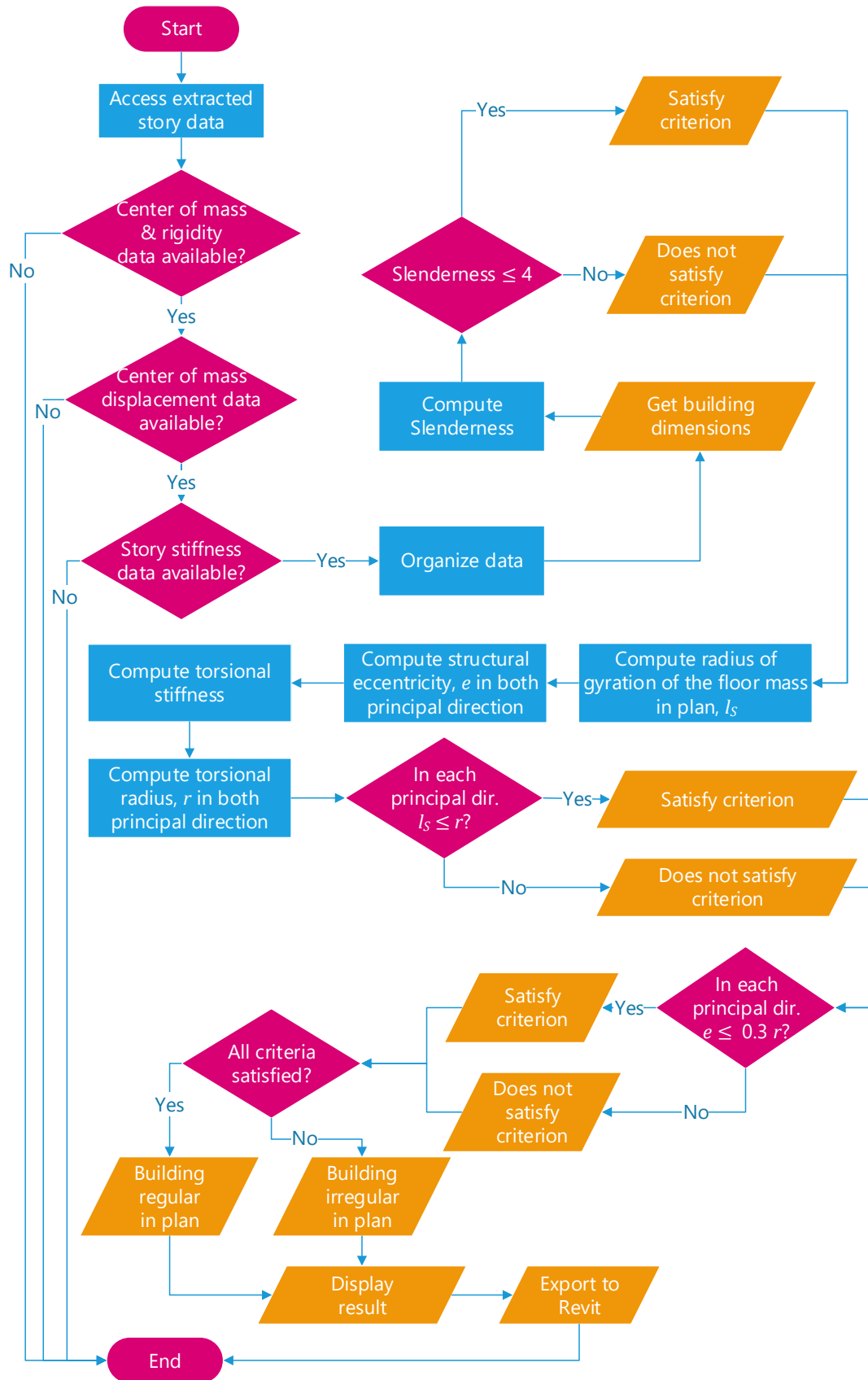
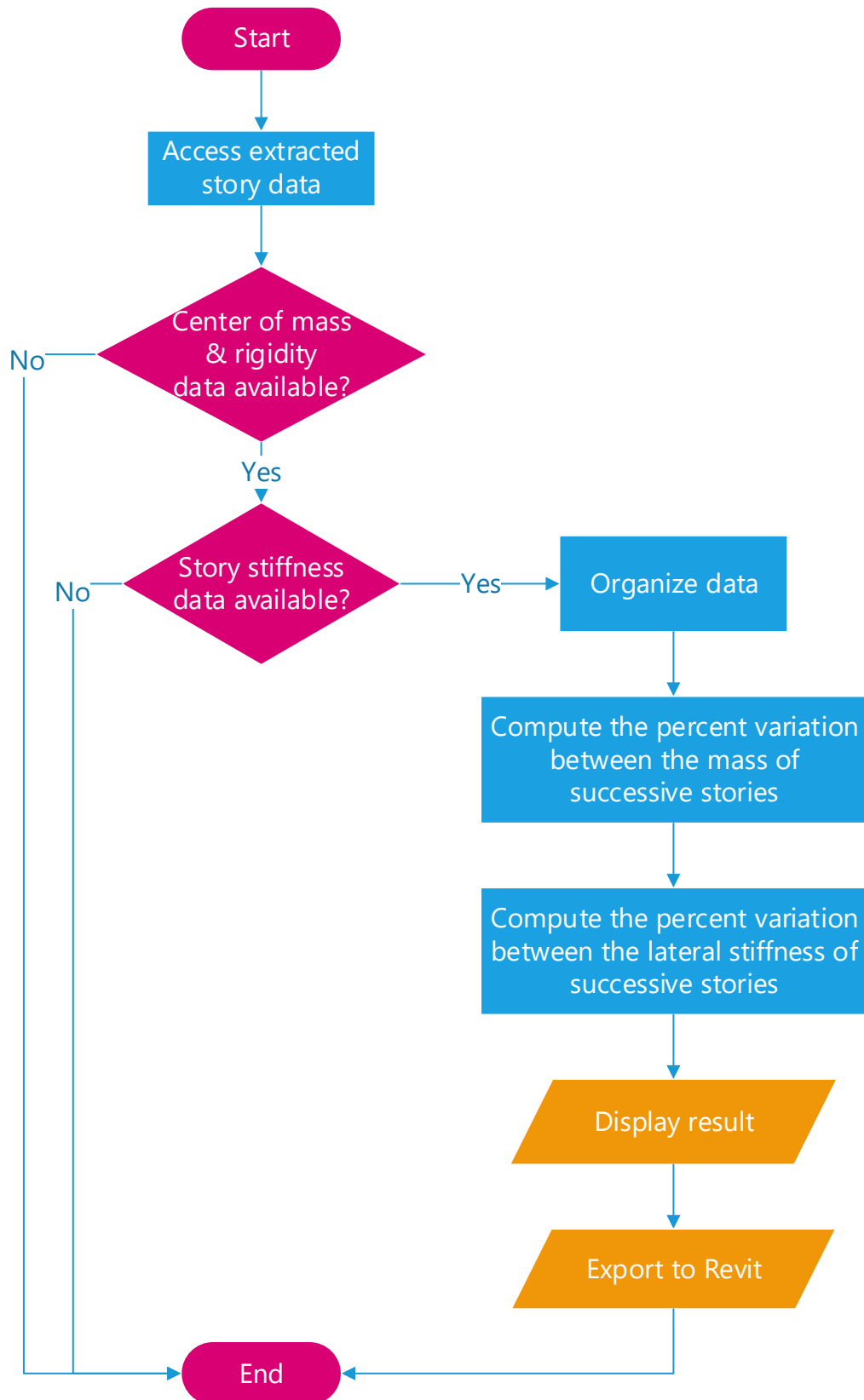


Figure 28: Plan regularity verification flowchart



**Figure 29: Elevation regularity verification flowchart**

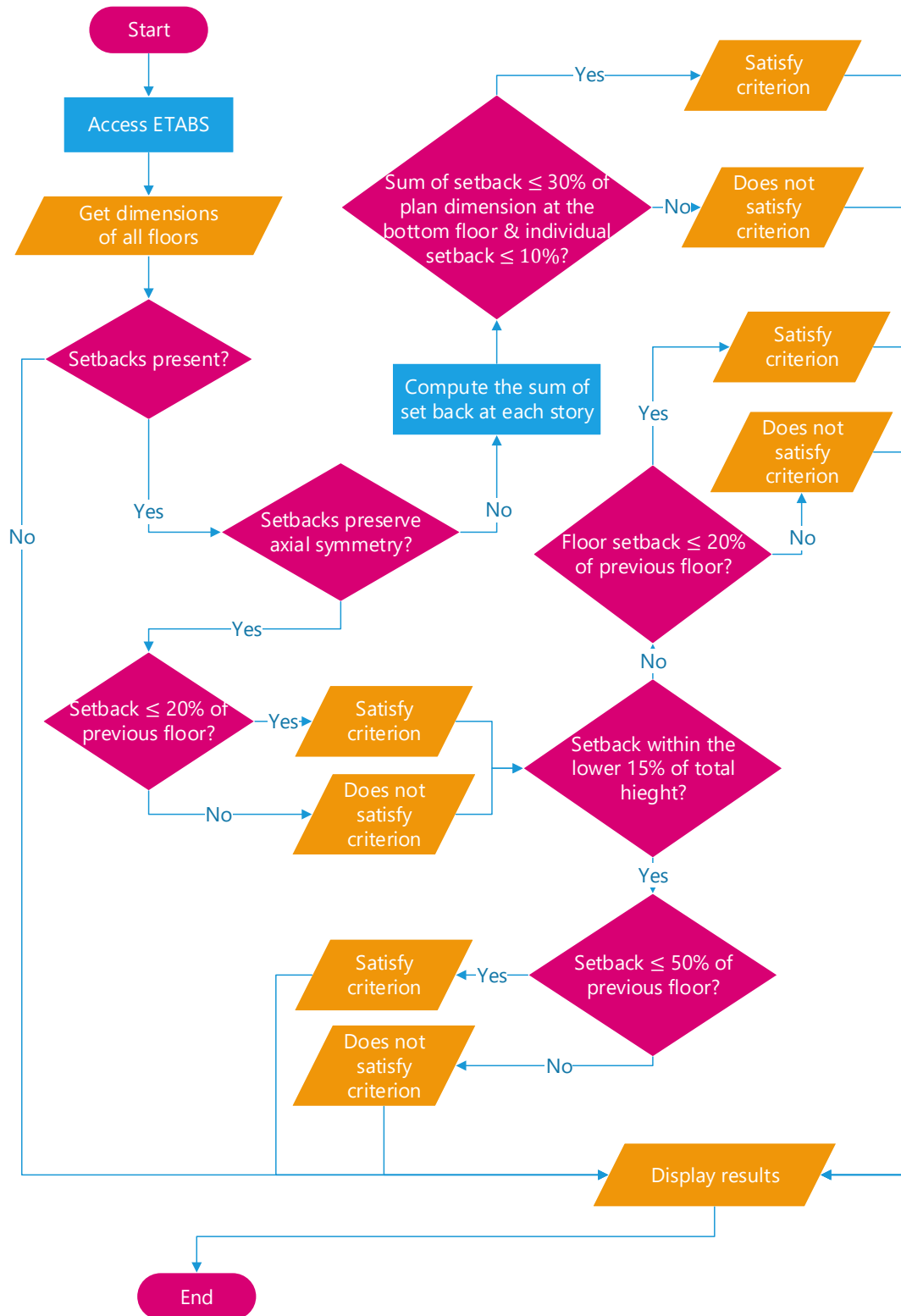


Figure 30: Additional elevation regularity verification flowchart

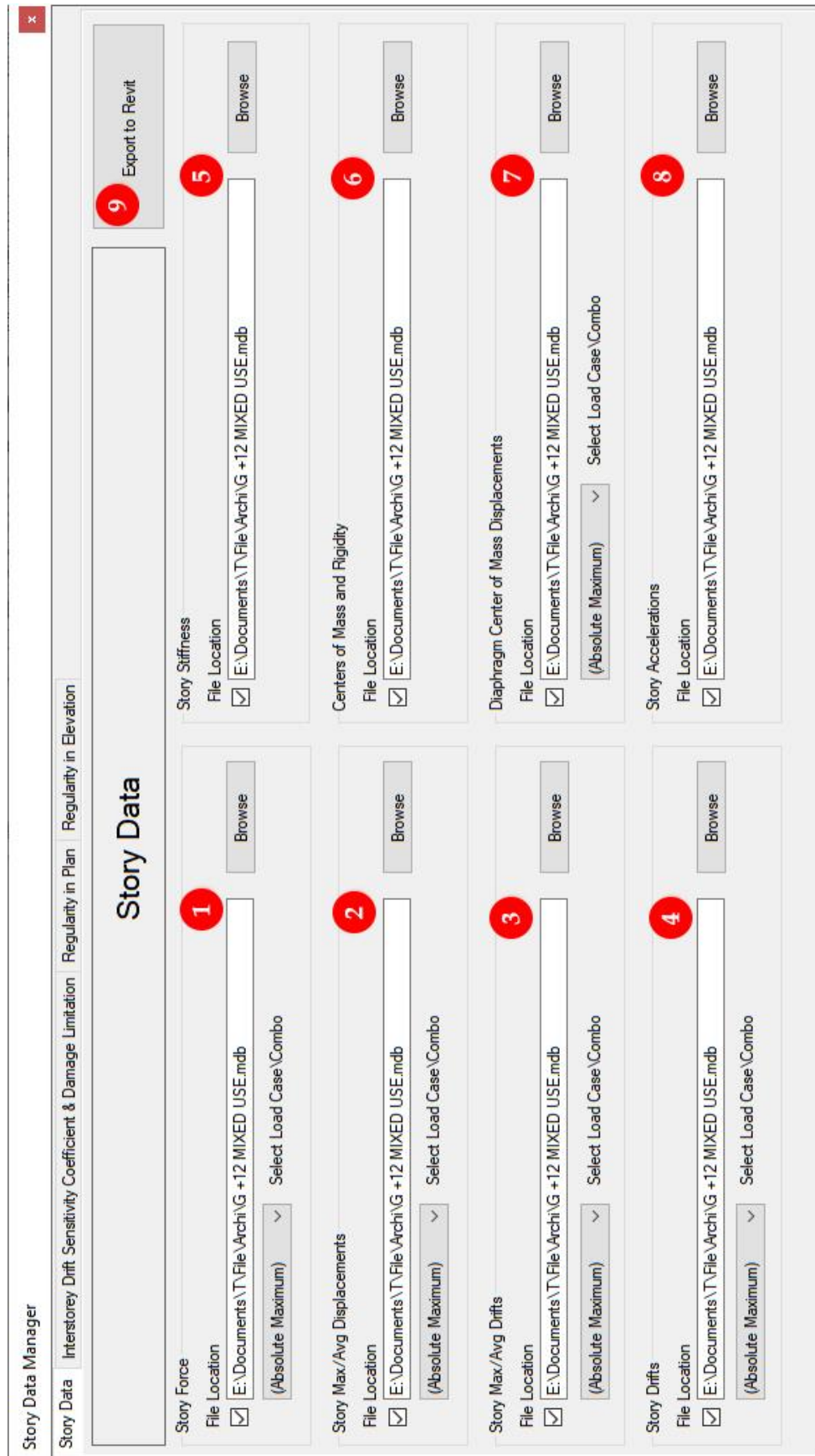


Figure 31: Story data manager tool GUI: Data extraction

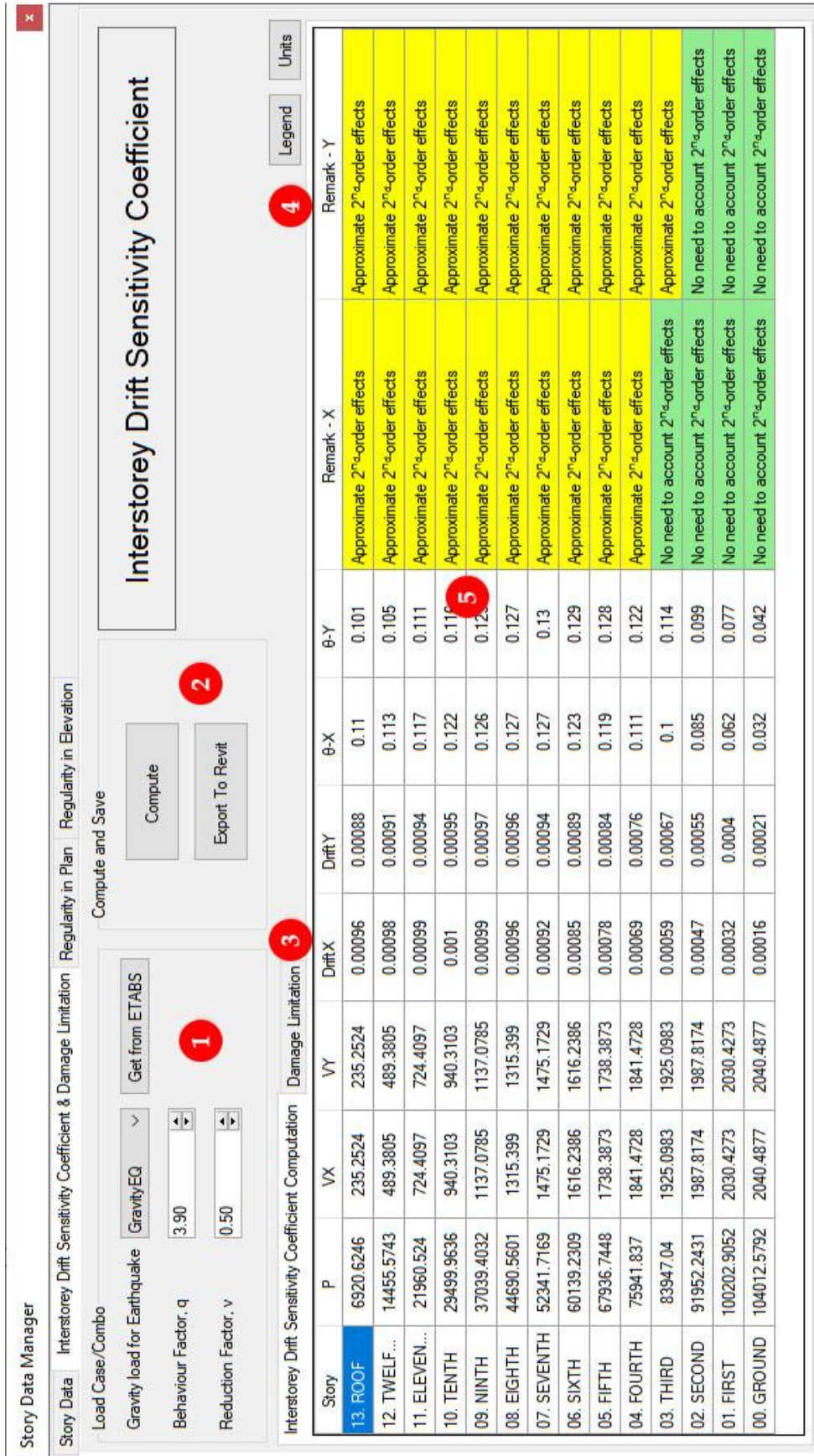


Figure 32: Story data manager tool GUI: Inter-story drift sensitivity coefficient computation



Figure 33: Story data manager tool GUI: Regularity in plan

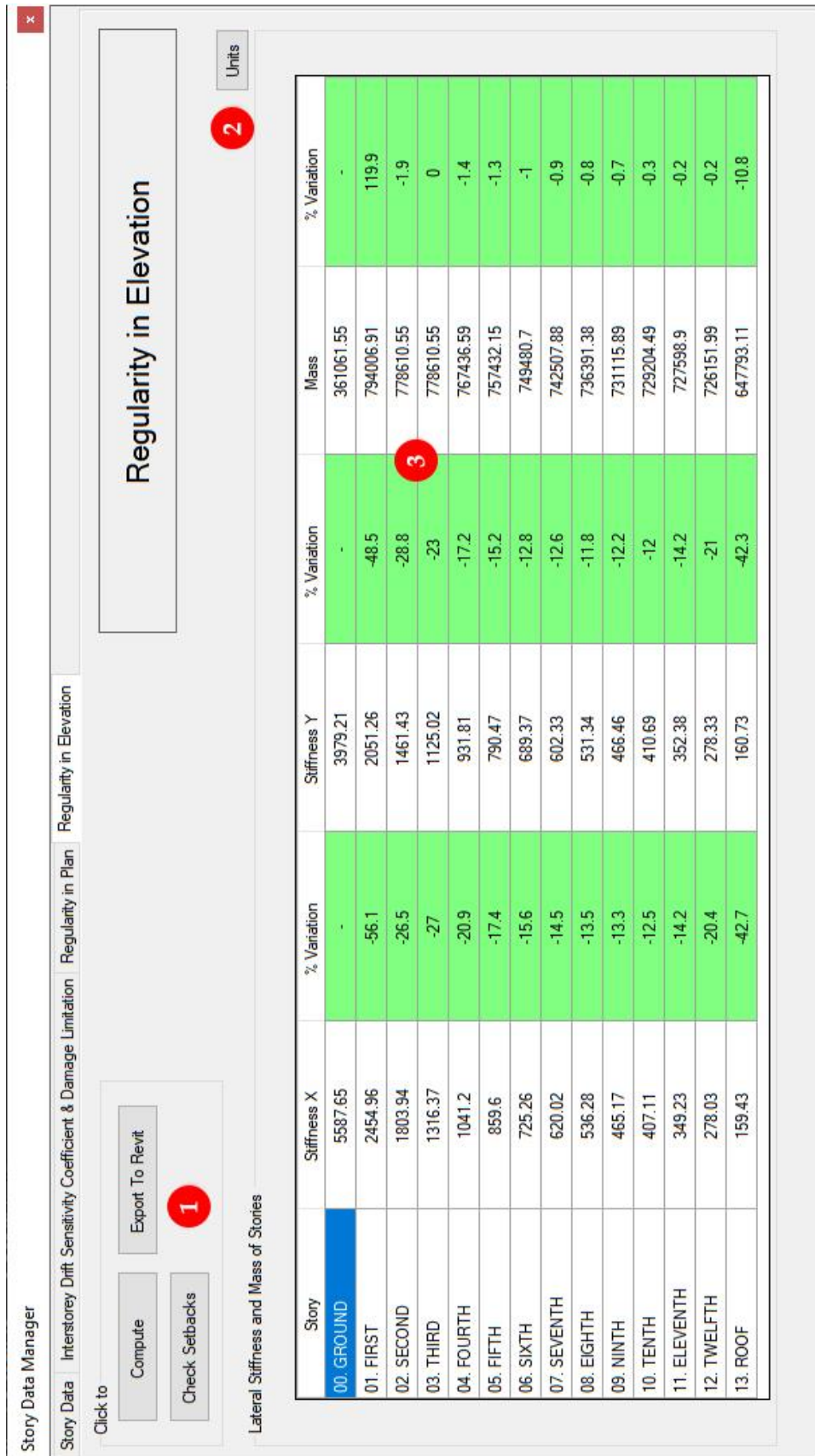


Figure 34: Story data manager tool GUI: Regularity in elevation

Figure 25 presents the workflow of the data extraction task. Figure 31 shows the graphic user interface (GUI) of the tool. The first tab of the tool is where story data extraction is carried out. Eight areas are denoted on the figure showing where the location of the ETABS output files can be provided. The located data is extracted and organized into acceptable form. Finally, the data is exported for Revit uptake in SBIM (\*. SBIM) file format by using the button at Area 9.

The second tab of the tools is where inter-story drift sensitivity coefficient  $\Theta$  and damage limitation check is carried out. To determine the inter-story drift sensitivity coefficient  $\Theta$ , the tool uses the procedure discussed on section 4.2.2. Figure 26 illustrate the work flow of task of computing inter-story drift sensitivity coefficient. The story data extracted by the tool on the previous step is used here. Therefore, no story data input from the user is necessary for this task and the tasks to come hereafter.

The tool will pull out all the defined load combination in the ETABS model and lists them on the user interface (Figure 32: Area 1). Then, the engineer is required to select the load combination that represent the gravity load for earthquake. The engineer is also required to provide the displacement behavior factor, since this information is not accessible from ETABS.

When the “Compute” button (Figure 32: Area 2) is pressed, the tool will then use the load combination selected by the engineer as the gravity load for earthquake, to extract  $P_{tot}$  from the story force data for each floor. It will also extract the seismic shear force from the story force data and the inter-story drift from story drift data in both orthogonal directions for each floor. Then, using equation (2), the tool will calculate inter-story drift sensitivity coefficient  $\Theta$  for each floor. Lastly, using the value of  $\Theta$ , the tool will reach a conclusion regarding consideration of second order effects.

The result of inter-story drift sensitivity coefficient for each floor along with the associated remark, are displayed on a table on the user interface of the tool (Figure 32: Area 5). The table is color coded based on the remarks. Green if 2<sup>nd</sup> order effects can be ignored, yellow if they can be approximate based on the provisions on the code, blue if they need to be computed and red if the structure is not stable. Area 4 on the GUI is where the units of the parameters shown in the table can be referred. At the same area a legend is provided.

The other tab of the second tab of the tool (Figure 32: Area 3) handles damage limitation requirements. Its workflow can be seen on Figure 27. The engineer is required to provide a reduction factor,  $\nu$  (Area 1). This value is set at 0.5 by default to reflect the recommendation of EC8 Part 1 Section 4.4.3.2(2). Then the calculation discussed on section 4.2.3, that verifies whether damage limitation requirements are satisfied, is carried out. Based on the result, remarks are made and presented on a table on the tools user interface. Finally, the tool concludes by exporting the determined parameters for inter-story drift sensitivity coefficient and damage limitation to Revit (Figure 32: Area 2).

Figure 28 presents the flowchart used by the tool to check regularity in plan. It begins by making sure all required data are available. From the ETABS model the tool will acquire the buildings dimension and compute slenderness and radius of gyration of the floor mass in plan. (See Equation (7) and (17)). Structural eccentricity (see section 4.2.4.1.1) and torsional radius (see section 4.2.4.1.2) are also computed.

Finally, the tool will check the three conditions for plan regularity (see section 4.2.4.1). If all the conditions are satisfied in both orthogonal directions of a particular floor, that floor will be declared regular in plan. And if at least one condition is not satisfied, the floor is declared irregular in plan. All of the parameters determined for plan regularity verification are displayed in tables on the tool's user interface, and they are exported to Revit.

Figure 33 presents the graphic user interface of the tool. Area 1 is where the main functions of the tool are executed. On Area 2, the tool will state whether the structure is regular in plan or not after concluding the computations. Area 3 shows five tabs where the values calculated for checking plan regularity are presented. As usual units are given (Area 4) and the tables are presented on Area 5.

On Figure 29 and Figure 30 present the tool's workflow for verifying some of the criteria for regularity in elevation. The tool will perform two tasks here. First, as shown on Figure 29, it will determine the percent variation between the mass and lateral stiffness of two successive floors and presents the result. The engineer is then expected to reach a conclusion by assessing these results based on EC8 Part 1 Section 4.2.3.3(3).

Afterwards, as shown on Figure 30, the tool will check for setbacks. To do this it will first retrieve story dimensions from ETABS and check for setbacks. If setbacks are present, the tool will make the verification laid-out on EC8 Part 1 Section 4.2.3.3(5). (See section 4.2.4.2 of this thesis)

If the structure fails to meet the one or both of the criteria discussed on the previous paragraphs, it can be concluded irregular in elevation. If both criteria are met, further visual inspection is need to verify regularity in elevation Section 4.2.4.2 of this thesis discusses these criteria.

Figure 34 shows the graphic user interface of "Regularity in Elevation" tab of the story data manager tool. Area 1 is where main functions are excited. The results are presented on Area 3 with their associated units available through the button on Area 2. On the model, whose results are currently shown, the ground floor slabs are not drawn. Thus, the mass of the ground floor is significantly lower than the next floor. For the rest of the floors, mass and lateral stiffness inclined gradually.

### ***5.3.2.2 Modal Analysis Manager Tool***

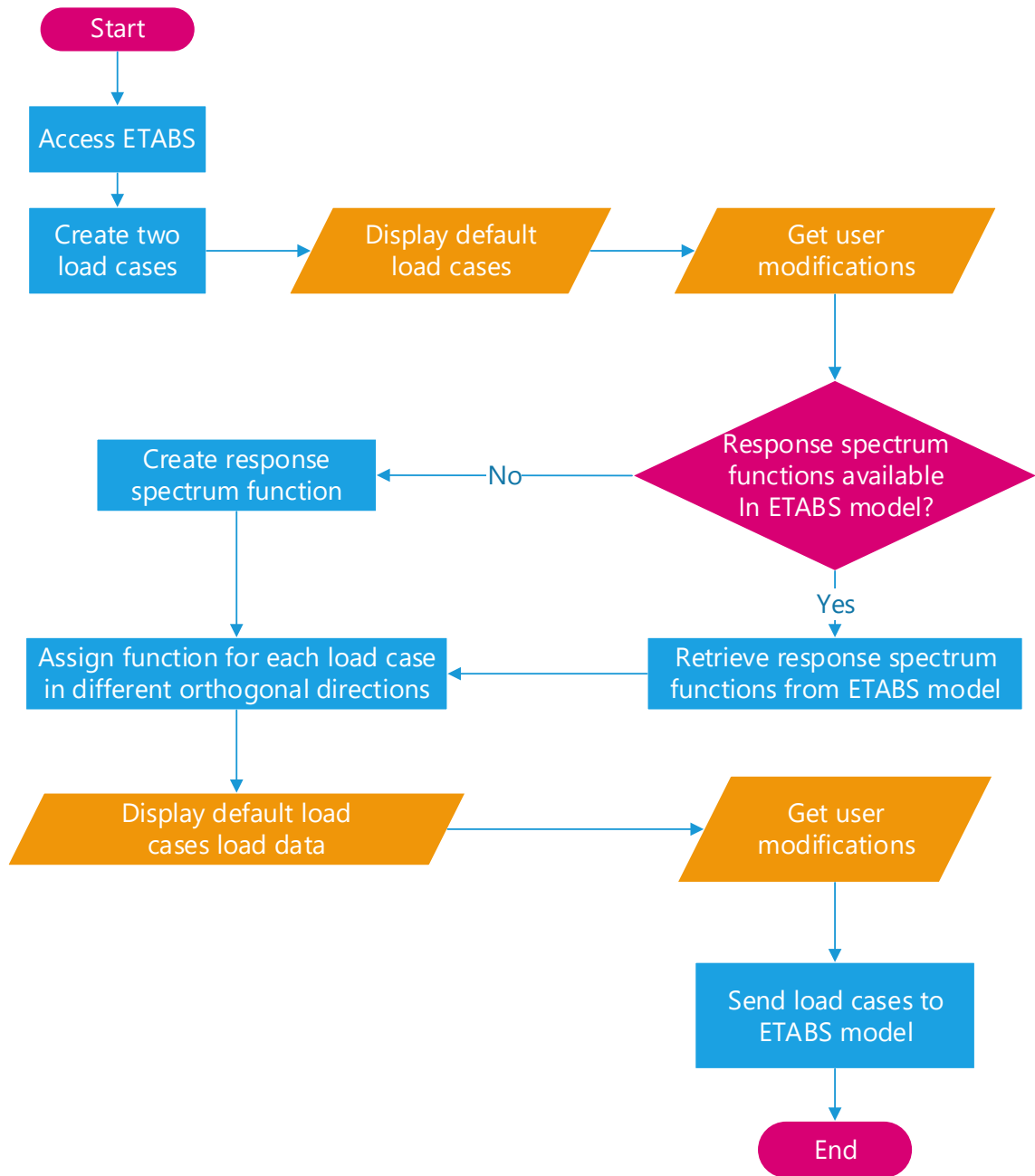
On section 4.2.1 of this thesis, the condition that calls for modal response spectrum analysis were discussed. The section also discussed the conditions the modal analysis should satisfy (EC8 Part 1 Section 4.3.3.3.1(3)).

Figure 35, Figure 37 and Figure 38 present the flowchart of the modal analysis management tool. The tool will begin by defining two response spectrum load cases for each principal direction (EX & EY). More response spectrum load cases can be added by the engineer. From ETABS, the tool will retrieve response spectrum functions. If none are defined, the tool will automatically create one. The content of the response spectrum function cannot be modified through API thus it has to be manually adjusted. Afterwards, the tool will automatically provide the load case data for each response spectrum load case. Finally, the response spectrum load cases are applied to the ETABS model.

The tool will create load combination containing the dynamic load cases. It will define eight combinations, containing a gravity load for earthquake, 100% of the response spectrum load case of one orthogonal direction and 30% of the response spectrum load case of the other orthogonal direction. These values are filled automatically and can be modified by the engineer.

After the modal response spectrum analysis is run, the tool will check whether the analysis satisfies the conditions for modal analysis set by the code (see section 4.2.1). The tool connects to the ETABS and pulls out the “Modal Participating Mass Ratios” data. The sum of participating mass ratio of the modes, in each principal direction should be greater than 0.9 (90%). The tool will assess this and presents the result (“ok” if the condition is satisfied and “Not ok” if not satisfied).

The tool will also compare the base shear result of the dynamic analysis with the static analysis, and determine the ratio of the two values. This ratio is used as to multiply the scale factor of the response spectrum load cases’ loads. The tool will apply this to the ETABS model and the modal analysis is performed again.



**Figure 35: Modal Analysis Manager tool flowchart: defining response spectrum load cases**

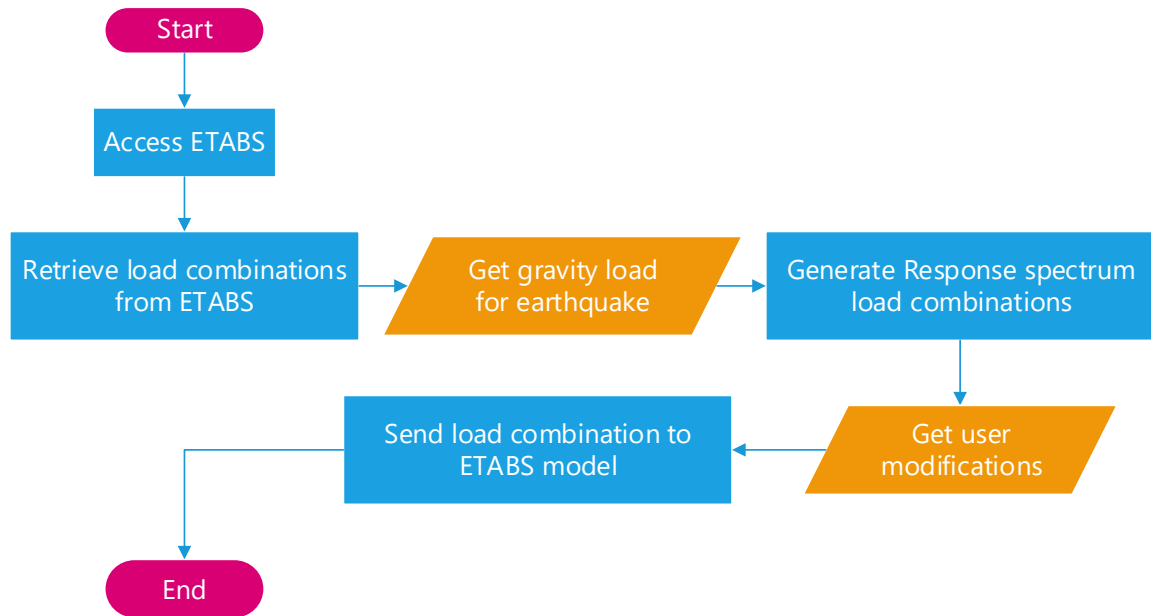


Figure 36: Modal Analysis Manager tool flowchart: Defining load combination

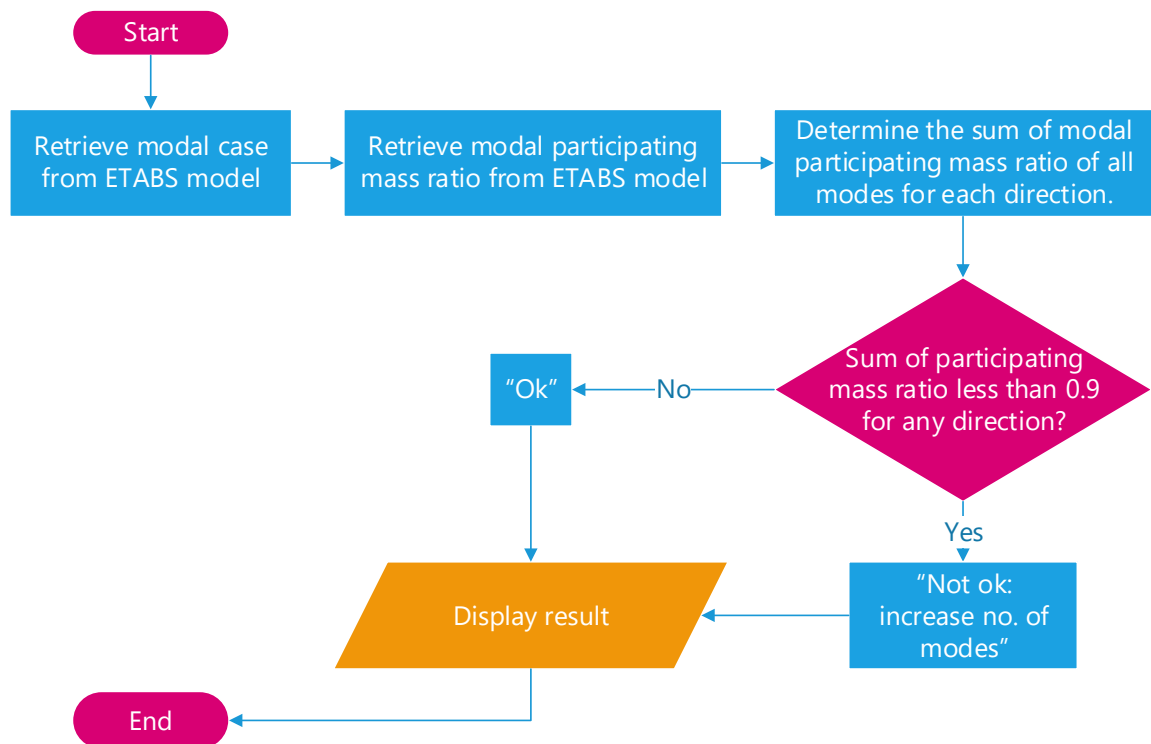
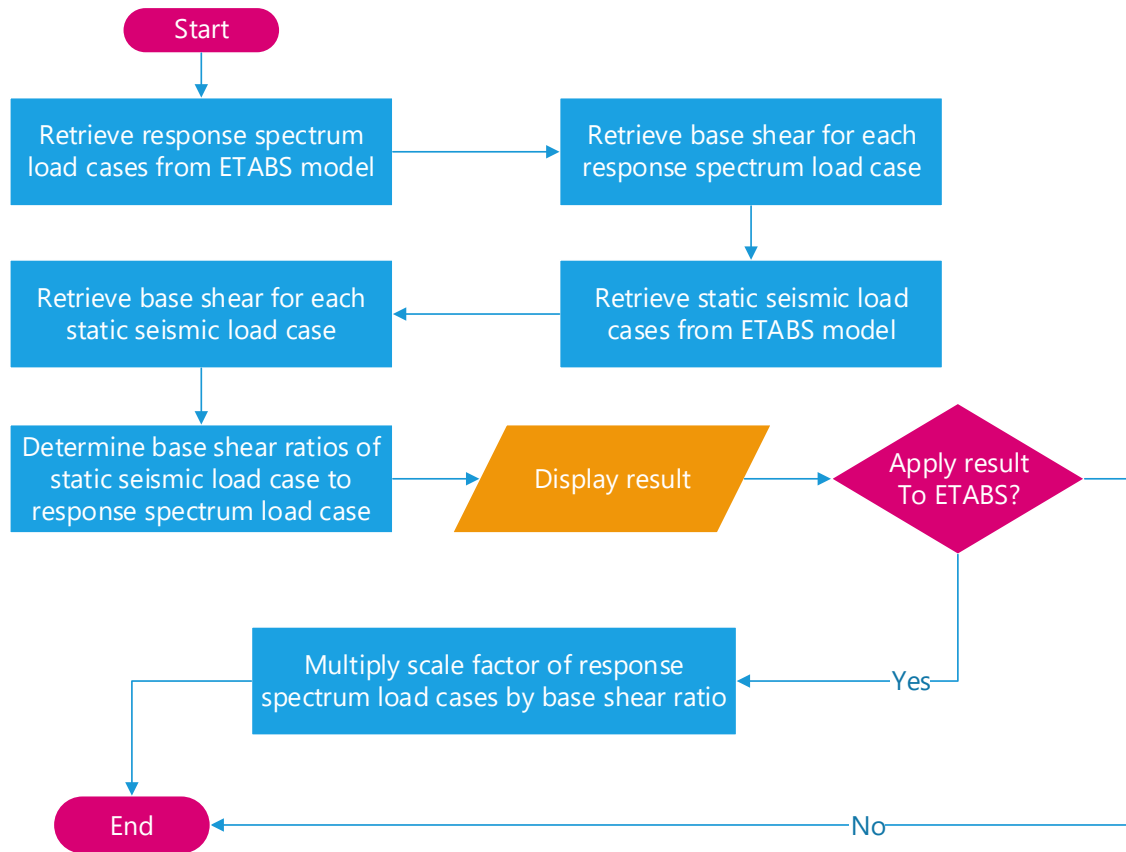


Figure 37: Modal Analysis Manager flowchart: Checking modal mass participating ratios



**Figure 38: Modal analysis tool flowchart: Verifying base shear**

Figure 39, Figure 40 and Figure 41 present the graphic user interface (GUI) of the modal analysis management tool. Figure 39 is the tab where response spectrum load cases are defined. On Area 1 dynamic load cases created by the tool are listed. When a response spectrum load case is selected on Area 1, its load case data are shown at Area 2. Finally, the defined parameters are sent to ETABS (Area 3).

Figure 40 shows the load combination tab of the tool. Area 1 is where the load combinations from ETABS are retrieved and listed so that the engineer can specify the gravity load for earthquake. If such load combination does not exist, it is created. By clicking the “Generate” button, response spectrum load combinations are automatically generated and listed at Area 2. When one combination is selected, the load cases within it are listed on Area 3. Finally, the result is sent to ETABS (Area 4).

The final tab of the tool is presented on Figure 41. The modal case is retrieved from ETABS at Area 1 and the modal participation check is executed on Area 2. After the base shear check is carried out, the resulting scale factors for each response spectrum load case are presented at Area 3.

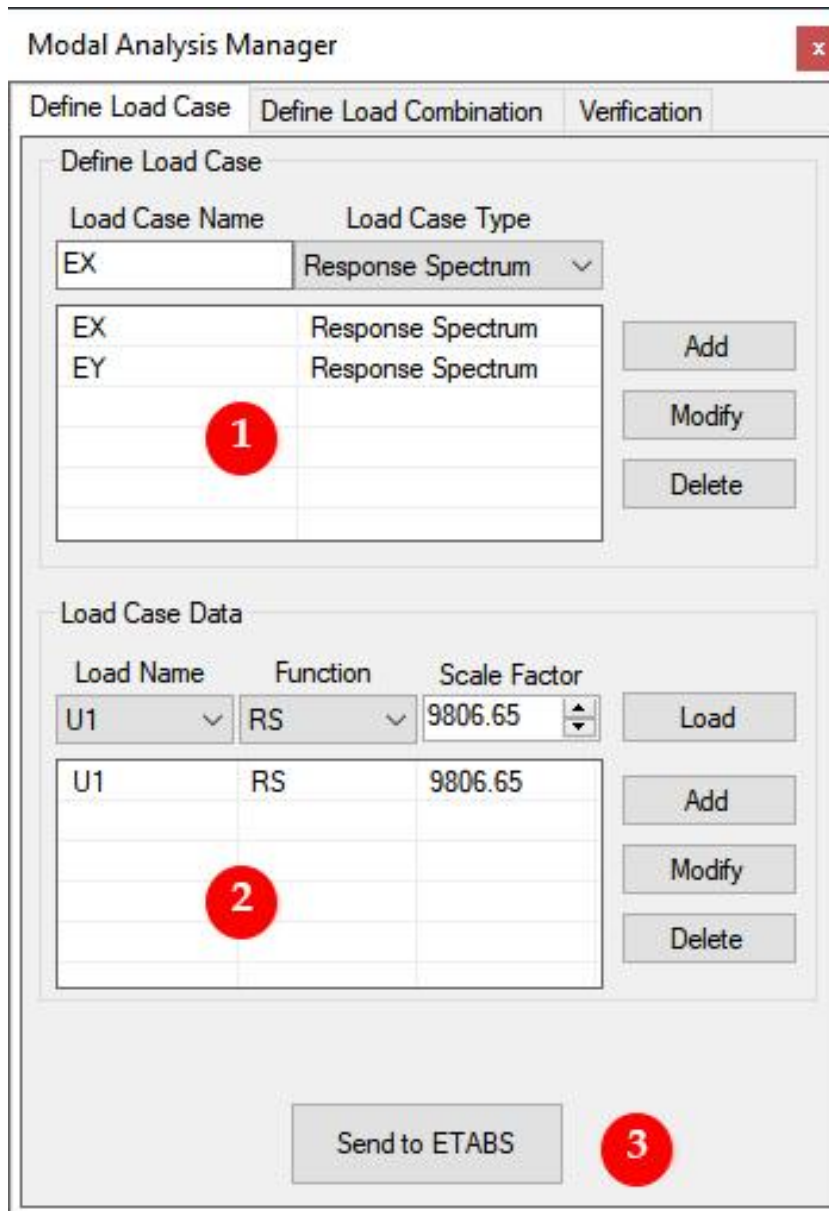


Figure 39: Modal analysis management tool GUI: Creating response spectrum load cases

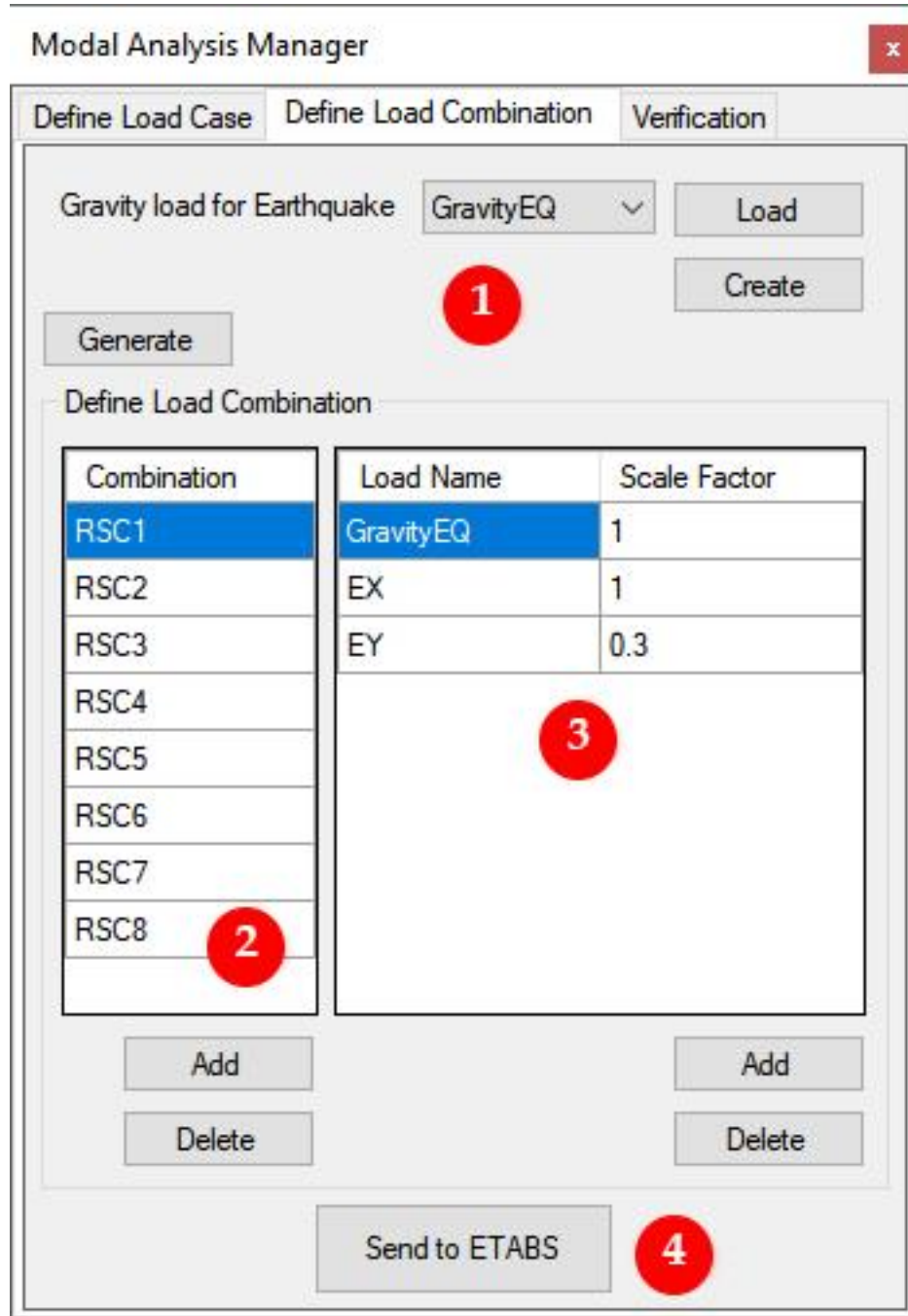


Figure 40: Modal analysis management tool GUI: Creating response spectrum load combinations

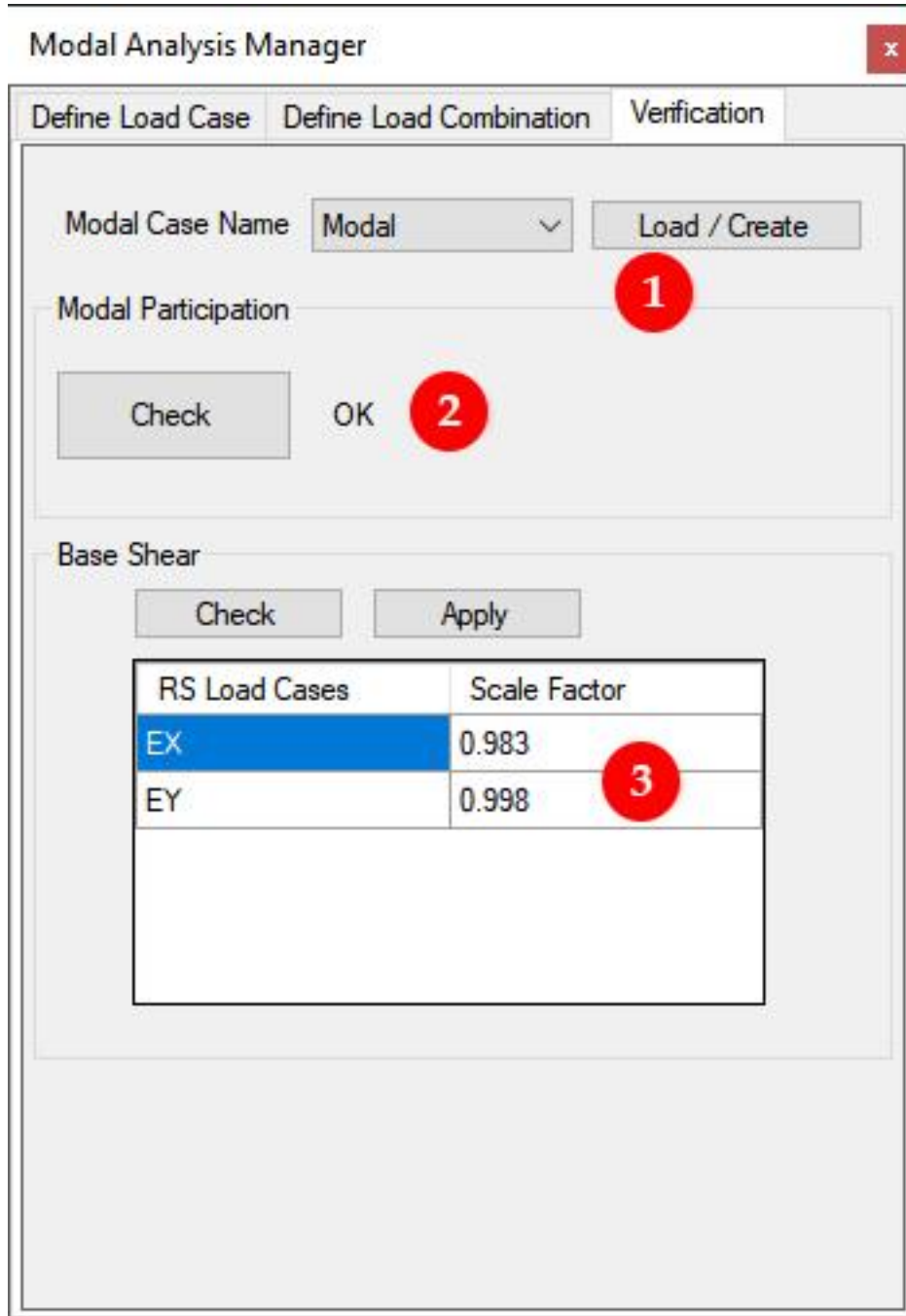


Figure 41: Modal analysis management tool GUI: Checking modal analysis conditions

### **5.3.2.3 Wall Analysis and Design Manager tool**

This tool was developed to extract analysis and design data for all structural walls, determine a rebar set and export the result. The result later will be read by a Revit plugin that will store the data on the central model. The tool will handle, pier and spandrel type walls (see Figure 11 and Figure 12).

The flowchart of the “Wall Analysis and Design Management” tool can be seen on Figure 42. The tool begins by accessing ETABS retrieving the list of all wall object in the model. From the list, the tool will look for piers. If there are any, the list of pier type wall objects along with their associated data, such as forces, stresses and strains, is retrieved.

Afterwards, the piers are divided based on their pier section type. For the uniform reinforcing pier section types, the tool will compute the longitudinal and transversal rebar set. These computations are based on the engineer’s preferences to be input in the tool. The resulting rebar set is presented on the corresponding table. The engineer is allowed to make changes to the rebar set.

After dealing with the uniform reinforcing pier section types, the tool will deal with simplified C & T pier sections. The steps followed are similar to the uniform reinforcing pier section type. Likewise, for spandrel type walls, their associated data is retrieved; using the engineer’s input, longitudinal and transversal rebar set is computed and displayed for user review and modifications.

Lastly, when the calculation for all wall types is completed, the result is exported to Revit in SBIM file format

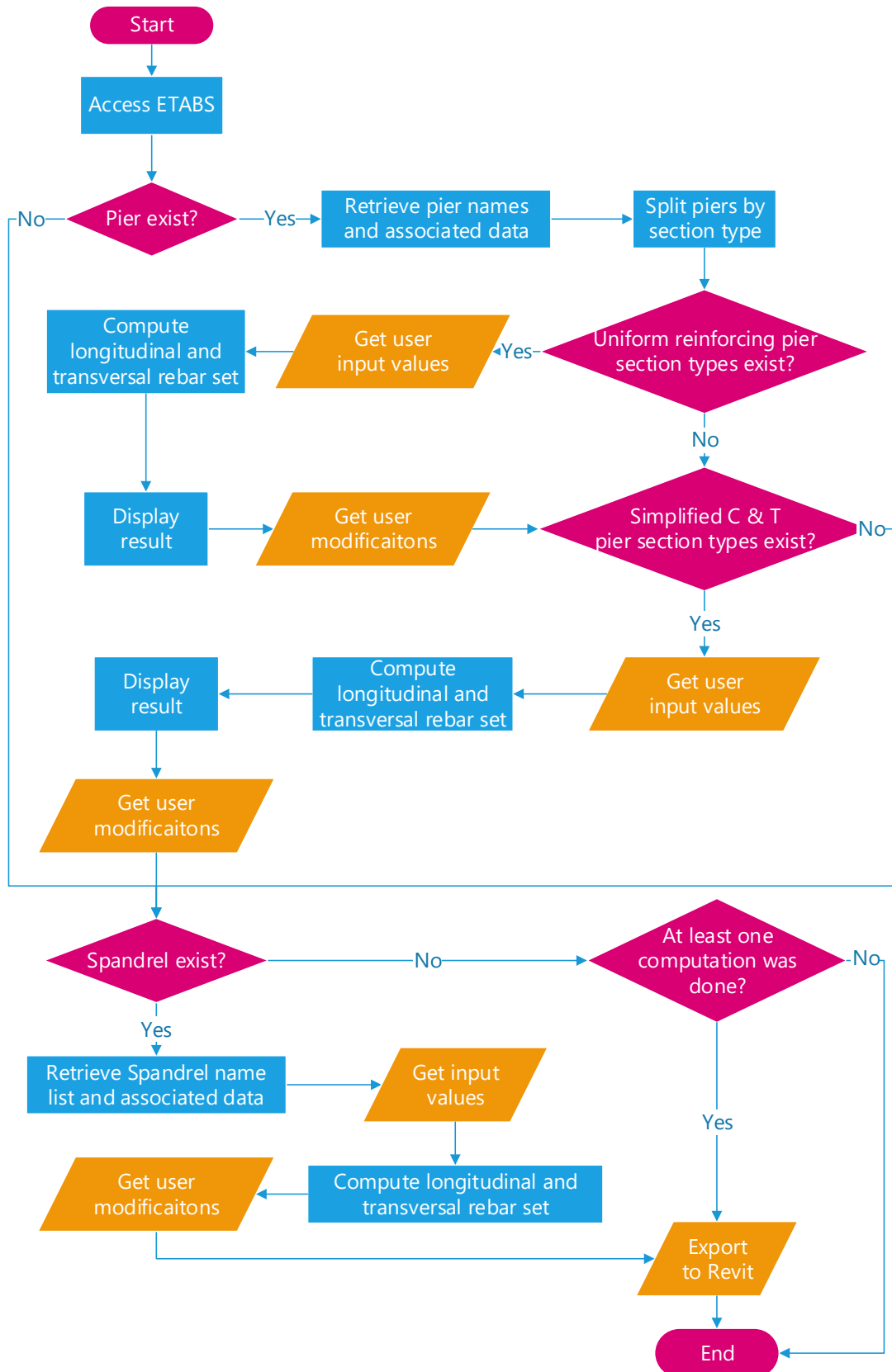


Figure 42: Wall Analysis and Design Manager tool flowchart



Figure 43: Wall Analysis and Design Manager tool GUI

Figure 43 presents the user interface of the “Wall Analysis and Design Manager” tool. Area 1 is where the basic commands located. The “Import Data” button will import all wall design data from ETABS. These data will include design warnings as well.

Using the wall design data and the user rebar preference values provide on Areas 3 – 6, the required rebar set for all walls (pier and spandrel) will be determined. The result is presented for each wall type separately in a table (Area 9 & 11). These tables are uniform reinforcing pier section type, simplified T & C pier section type and spandrel. Filters (Area 8) are provided to assist in reviewing the results. One filter for each three result tables is provided. The units can be seen by using the “Units” button provided at Area 10.

At area 7, two buttons are provided for the engineer to specify a set of rebar diameters. One is for longitudinal bars and the other is for transversal bars. The tool will use the minimum bar diameter specified and if the resulting spacing is below the specified minimum spacing, it will skip to the next bar size from the list provided. Similar feature is included on the other tools that handle rebar.

The engineer may change the rebar set preferences at any time and run the computation again with the “Reanalyze” button (Area 1). Furthermore, the output table allows the engineer to provide rebar set (Green area) so long as the provided rebar set complies with the required rebar set.

Area 2 is designated for analysis results. The tool will retrieve all the load combinations used for wall analysis from ETABS. The engineer will select a load combination, and the tool will retrieve the analysis results of that combination for each wall in the model. The analysis results retrieved are wall forces, stresses and strains.

Finally, the computation results, the user modifications and the analysis results are saved in SBIM file through the “Save and export” button (Area 1). This file will later be read by a Revit plugin and its content will be uploaded onto the central model. This file can also be used by the wall design manager tool, to continue making modification by loading it into the tool using “Load” button (Area 1).

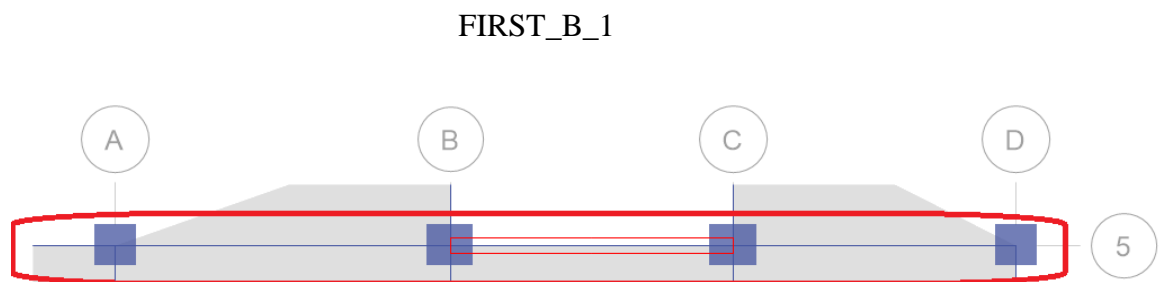
#### 5.3.2.4 *Beam Design Manager tool*

The flowchart of this tool is given on Figure 45. The application begins by accessing ETABS and exposing all frame data in ETABS. Several information is collected about each individual object from ETABS. For the functions of this tool, object unique name, story name, X, Y, Z coordinate of start and end points of frame objects along with their name are used.

##### 5.3.2.4.1 Beam grouping

The next task is screening out columns so that beams only remain. Then, the beams are arranged by the story level on which they are found. Then the beams are further organized in X and Y direction. Afterwards, for both directions, the beams that lay on an axis are grouped together.

Each group of beams is named automatically. The name follows a specific format: it begins with the name of the story followed by the letter B and end with a number sequence. Each of these are separated by an underscore. The number sequence begins from the horizontal beam groups at the northern end to the ones at the southern end and then from the left vertical beam group to the right side. For instance, the name of a beam group (Figure 44) that is found on the first floor at the northern end has the following name:



**Figure 44: Example of a beam group**

If the application finds a beam whose Z coordinate values are not the same with the Z coordinate of the story, the application decides it is a landing beam and group it as such. If this assumption is not acceptable, the user can easily change the group.

This function will group all the beams in the entire model. However, the engineer is free to add more group or modify the generated groups as long as the naming follows the format specified previously. These groups are saved into the model and need not be done again unless beam configurations are changed.

#### 5.3.2.4.2 Retrieving beam design data

The application gathers design data for each beam individually and then determine rebar sets. At construction sites, it is customary to lay minimum top rebar from start to end (applying splice when necessary). Then additional bars are added at the support as required. The same method is implemented in the application. For each beam, ETABS provides three top reinforcement area values (at two ends and at the middle). The top middle reinforcement area of each beam in a group are taken and among them the maximum reinforcement area is selected. This reinforcement area is taken as the minimum top reinforcement area for the entire beams in the group.

Additional reinforcement bars required at support are then calculated. Neighboring beams may have different reinforcement area requirement at top adjacent supports. For the sake of construction, however, similar rebar set is placed at the top support between two beams by taking the maximum reinforcement area value.

ETABS returns three bottom rebar area for a single beam. The three rebar areas are changed into a single rebar area by taking the maximum amongst the three. Every single beam in the beam group is provided with a single bottom rebar area requirement. Through these processes, new adjusted rebar area requirements are computed for all beam objects.

Once all the longitudinal rebar areas are adjusted, bar diameter and number of rebar is computed. The engineer will provide a rebar set preference. Using these values, the application will determine the top and bottom rebar sets of all the beams in the model. Similarly, rebar set of stirrup bars are determined

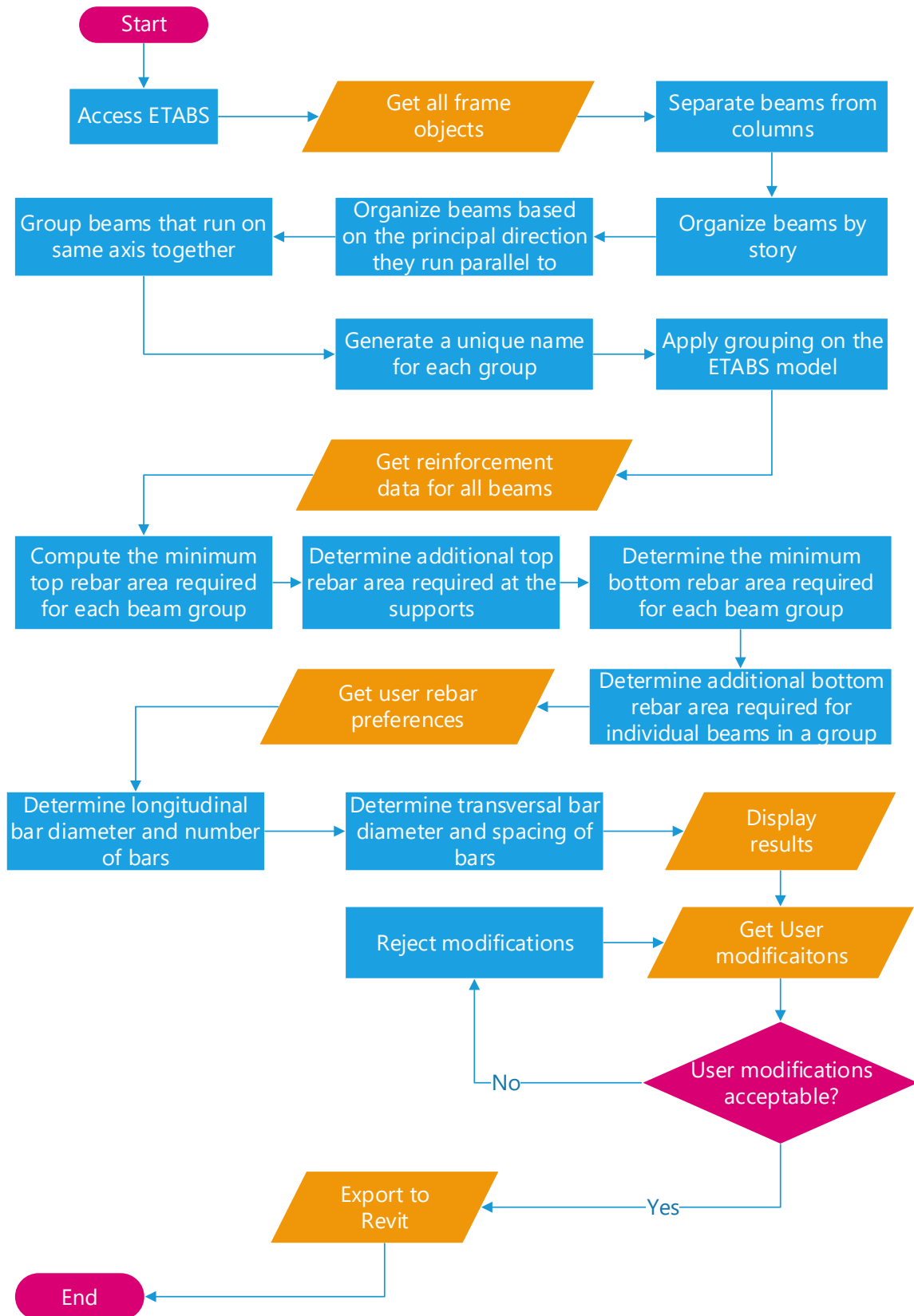


Figure 45: Beam design manager tool flowchart

Figure 46 presents the graphic user interface of the Beam design manager tool. Area 1 is where major functions of the tools are executed. “Import Data” button will, filter, organize and group beams. If the “Create Group” check mark is checked, the tool will apply the grouping in the ETABS model. The “Import Data” button, after grouping beams, will figure out the rebar set as explained in previous paragraphs.

Area 2 and 3 are where the engineer provides rebar preference. On Area 4, a set of rebar diameters to be used for longitudinal and transversal diameter can be provided. The tool will use these sets the same way as the “Wall Analysis and Design Manager” tool.

Area 8 is where the result is displayed. The display is divided into two section (Area 6) which are the longitudinal and transversal reinforcement. The engineer can see the required rebar set and provide a rebar set in the green fields. This value must comply with the required value calculated. Filters area provided at Area 5 and units at Area 7.



Figure 46: Beam Design Manager tool GUI

#### **5.3.2.5 Column Design Manager tool**

Figure 47 presents the flowchart of the “Column Design Manager” tool. The tool begins by pulling all frame objects in the model along with their associated data. Then the columns and their associated data are filtered out.

The tool organizes the columns by story. Then it goes to the last floor and get the name of each column in that level in order of location. Using these columns as a lower end, the tool then goes to successive levels, identifying columns that are connected to the columns on the previous floor. This process is done for each level on the model successively. At the end, these columns are assembled together to provide a column objects that run from the bottom level to the top. If some columns do not run to the top level, they will be detected by the tool.

After columns are assembled, longitudinal and transversal reinforcement data for each individual column object is pulled from ETABS.

The engineer is required to provide rebar set preference and using these preferences, longitudinal and transvers rebar sets are determined. The result is then presented on table. The engineer may modify a rebar set so long as it complies with the required rebar set. Finally, the tool will conclude by exporting all the data collected in SBIM file.

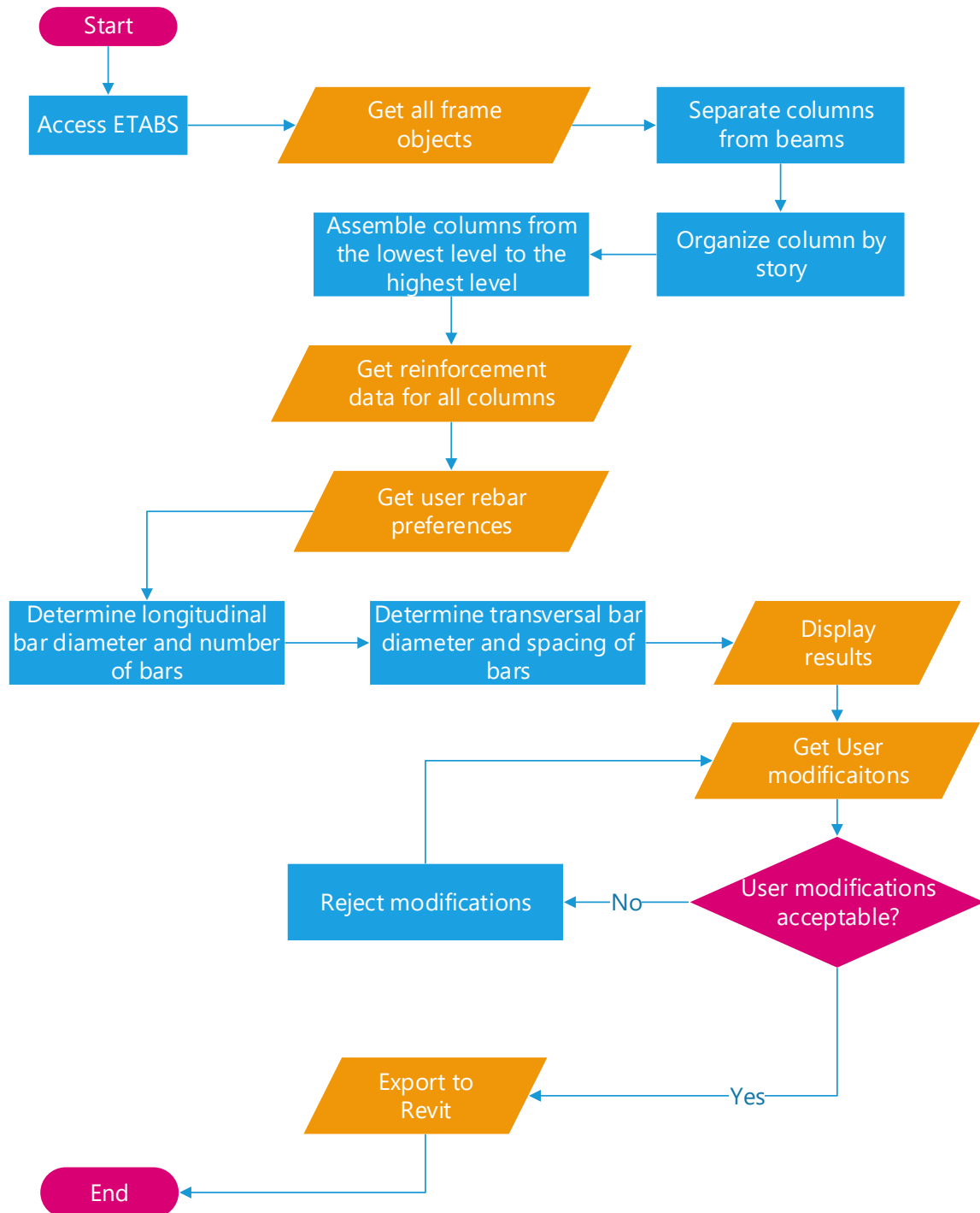


Figure 47: Column design manager tool flowchart

Figure 48 presents the graphic user interface of the “Column Design Manager” tool. Area-1 is where the button that execute the main functions of the tool are executed. The user preferences on Area 2 and 3 and the rebar diameter set at Area 4 are used when rebar sets are computed. The results are displayed on a table (Area 9) with their units given by the button “Units” (Area 8).

Using the “Automatically Group Columns” button (Area 5) the columns can be grouped based on their cross-section. Any value provided for a column object in a group will be copied to every other column object in that group. The filter provided at Area 7 enables users to filter the displayed result by column name or by column group name.

Whenever a rebar preference is changed, the computation can be run again using “reanalyze” button (Area 1). Finally using the button at Area 6, the collected and computed column design data is exported into Revit. The export file (SBIM file) can be loaded to the tool again for further data manipulation.

Column Design Manager

Click to Import and Organize Data Reanalyze

Filter Column Name (ALL) Group Name CG-3

Rebar Parameters

Longitudinal bars Minimum Diameter 14 Minimum Number 14 Maximum Number 16 Maximum Spacing Between Bars 25

Transversal bars Minimum Diameter 8 Minimum Spacing 100 Maximum Spacing 200 Spacing Round off 50

Column Grouping Automatically Group Column  Apply to ETABS Save / Export Load

Units

Column Reinforcement Data

Column Name	Group Name	Story Name	Unique Name	Section	Long. As	Bar Diameter	Required No. of Bars	Provided No. of Bar	Trans. At	Trans. Bar Diameter	Required Bar Spacing	Provided Bar Spacing
C-5	CG-3	13. ROOF	36844	C500X500	2500	16	14	14	0	8	200	200
		12. TWELFTH	36506	C500X500	2500	16	14	14	0	8	200	200
		11. ELEVENTH	36168	C500X500	2500	16	14	14	0	8	200	200
		10. TENTH	35830	C500X600	3000	16	16	16	0	8	200	200
		09. NINTH	35492	C500X600	3000	16	16	16	0	8	200	200
		08. EIGHTH	35154	C500X700	3500	20	16	16	0	8	200	200
		07. SEVENTH	34816	C500X700	3500	20	16	16	0	8	200	200
		06. SIXTH	34478	C600X800	4800	20	16	16	0	8	200	200
		05. FIFTH	34139	C600X800	4800	20	16	16	0	8	200	200
		04. FOURTH	33800	C700X900	6300	24	16	16	0	8	200	200
		03. THIRD	28798	C700X900	6300	24	16	16	0	8	200	200
		02. SECOND	28459	C700X900	6300	24	16	16	0	8	200	200
		01. FIRST	28020	C800X900	7200	24	16	16	0	8	200	200
		00. GROUND	5101	C800X900	7200	24	16	16	1304	10	100	100
C-8	CG-3	13. ROOF	36858	C500X500	2500	16	14	14	0	8	200	200

Figure 48: Column Design Manager tool GUI

#### **5.3.2.6 Slab Analysis and Design Manager tool**

The flowchart used by the slab design manager tool is presented on Figure 49. The tool begins by connecting with ETABS. Then, it will pull all the area objects defined in ETABS. Among these area object, the tool will filter out the floor area objects (structural slabs). The story level and thickness and the analysis results of each floor area is retrieved.

ETABS has two design basis for slab design: finite element based and strip based. The result of finite element-based design is not available through output tables. The strip-based design provides output tables and it can also be directly accessed from ETABS. The output is given for the design strips. However, the outputs do not link a design strip with the slab being design. Thus, the design results for slabs cannot be retrieved automatically. Consequently, the engineer is expected to manually provide design results to the tool.

The graphic user interface of the tool is shown on Figure 50. On the figure, Area 1 is where the main functions of the tool are executed. The “Import data” will retrieve all required slab data from ETABS. On area 2, the engineer will be able to provide a preferred rebar set. Using this value, the tool will populate the table (Area 8). Two separate tables, one for support reinforcements and the other for field reinforcement are, provided (Area 7).

Then the user will manually provide rebar area requirements on the table (yellow fields). Using these values along with bar diameters, the tool will compute rebar spacing (green fields). Conversely, the engineer may provide the rebar spacing and the tool can determine the provided rebar area.

A filter that organizes the display based on story is provided on Area 4 and the units can be seen using the “Units” button on Area 6.

If similar stories exist in the model, the tool can group them by using the button given on Area 3. ETABS gives identical slabs found at different story level identical label. These labels are used to group identical slabs by the tool. Any value provided for a slab object in a group will be copied to every other slab object in that group.

Area 5 is designated for analysis results (shell forces, stresses and strains). The tool will retrieve all the load combinations used for slab analysis from ETABS. The engineer will select a load combination, and the tool will retrieve the analysis results of that load combination for each slab object in the model.

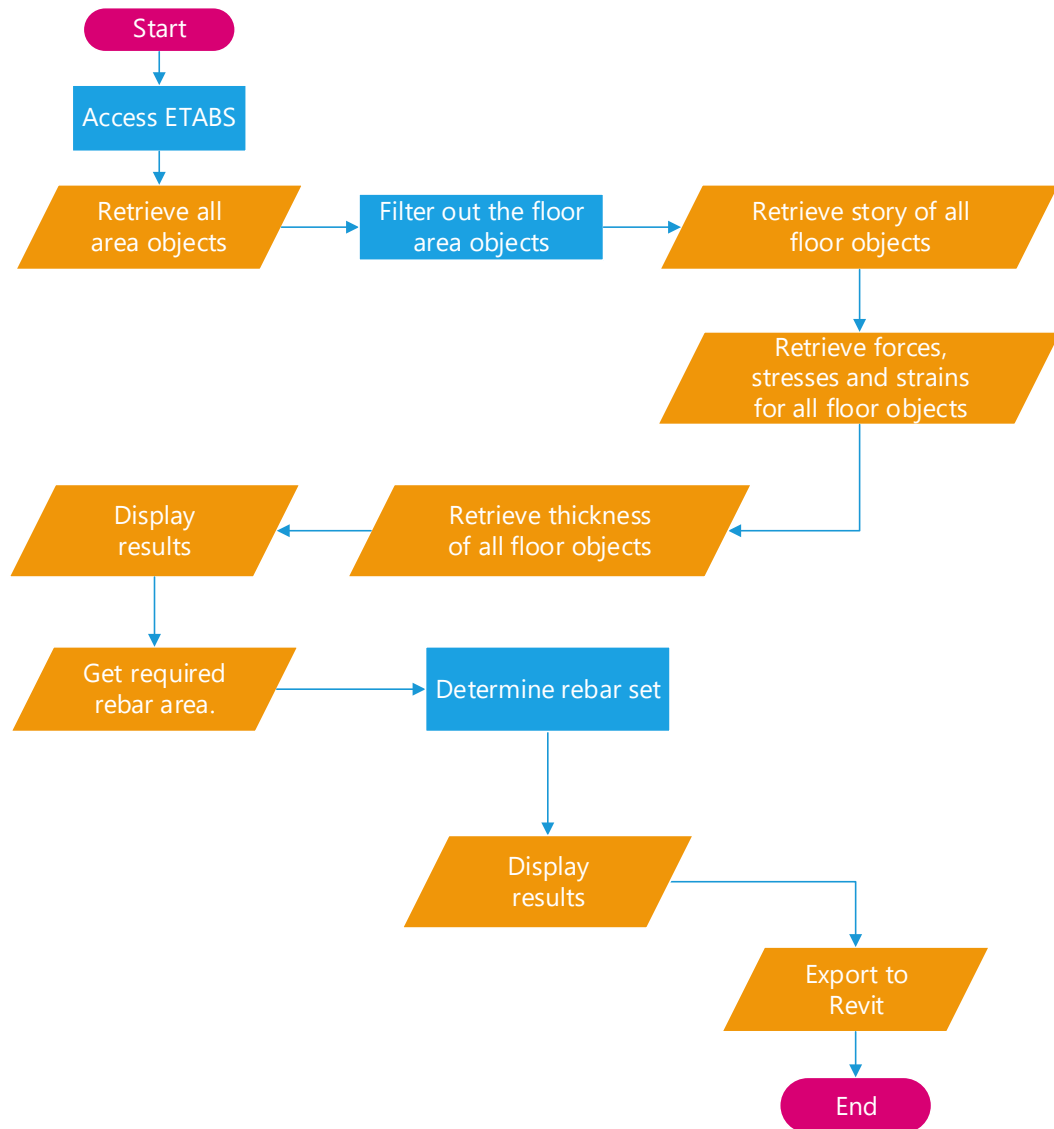


Figure 49: Slab Analysis and Design Manager tool flowchart

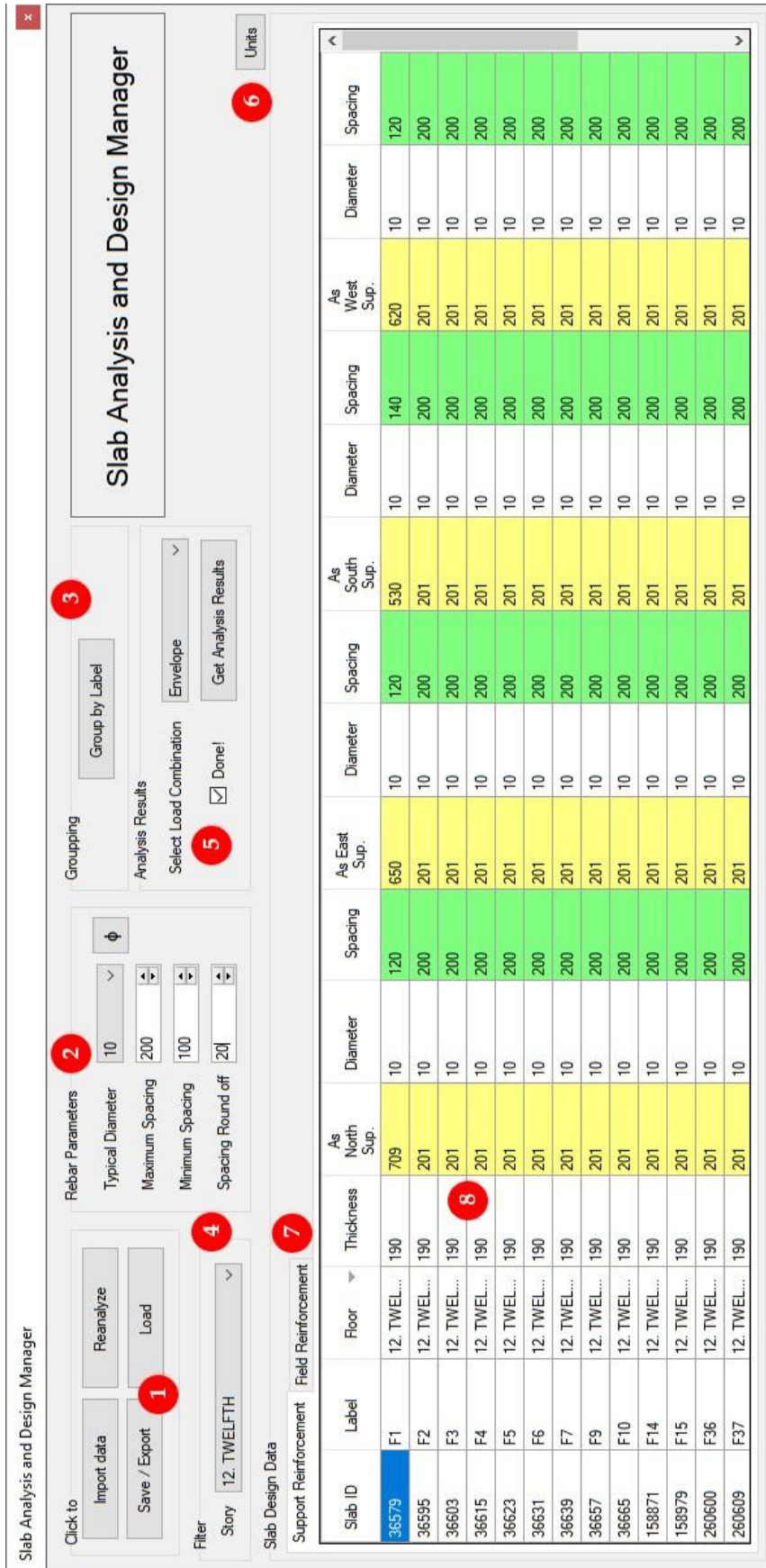


Figure 50: Slab Analysis and Design Manager tool GUI

### **5.3.2.7 Frame Design Forces Manager tool**

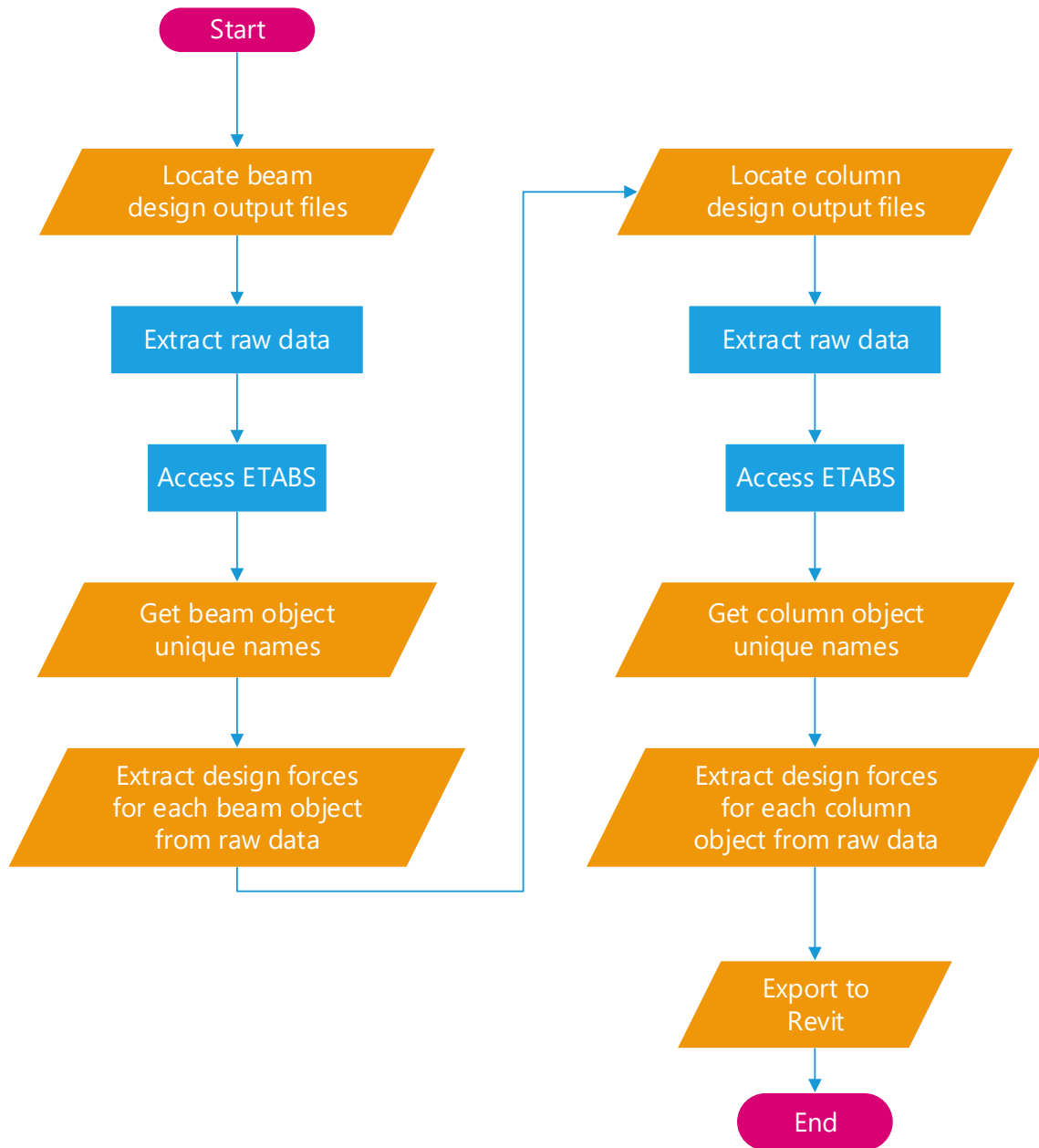
This tool will handle the design forces determined for frame objects, specifically beams and columns, by ETABS. These forces include axial forces, shear forces, bending moments and torsional moment. The design forces for slabs, walls and footings are extracted by the tools that were developed to manage the design of those elements.

The design forces of frame objects cannot be directly accessed from ETABS. Instead ETABS design output file will be used to gather these data. Figure 51 illustrates the flowchart of the frame design manager tool. The tool will begin by requesting the location of the design output files. The tool handles beam and column independently.

Once the ETABS design outputs files are located, the raw data is extracted. In the raw data, objects are identified based on their story and label and not by their unique id. The unique ids are the link connecting objects in ETABS model with their counterpart in the central model (See section 5.2). Thus, the unique id of all frame objects is extracted from ETABS along with label and story level. Using these three parameters, the raw data extracted from ETABS output files is associated with the unique id of each frame objects. Afterwards, the tool exports the design forces of all frame objects along with their unique id to Revit through SBIM file.

Figure 52 presents the graphic user interface of the “Frame Design Forces Manager” tool. Area 1 and 2 are the locations where ETABS design output files containing Beam data are provided. Likewise, Area 3 and 4 are the locations where ETABS design output file containing column data are provided. Each file location textbox has a check mark to its left. These will be automatically checked by the tool to confirm that an input file has been successfully located.

At Area 6, a “help” button is provided to give guidance in locating the appropriate files for tools. Afterwards, by pressing the “Export to Revit” button (Area 5), the tool exports the design forces to Revit.



**Figure 51: Frame design forces manager tool flowchart**

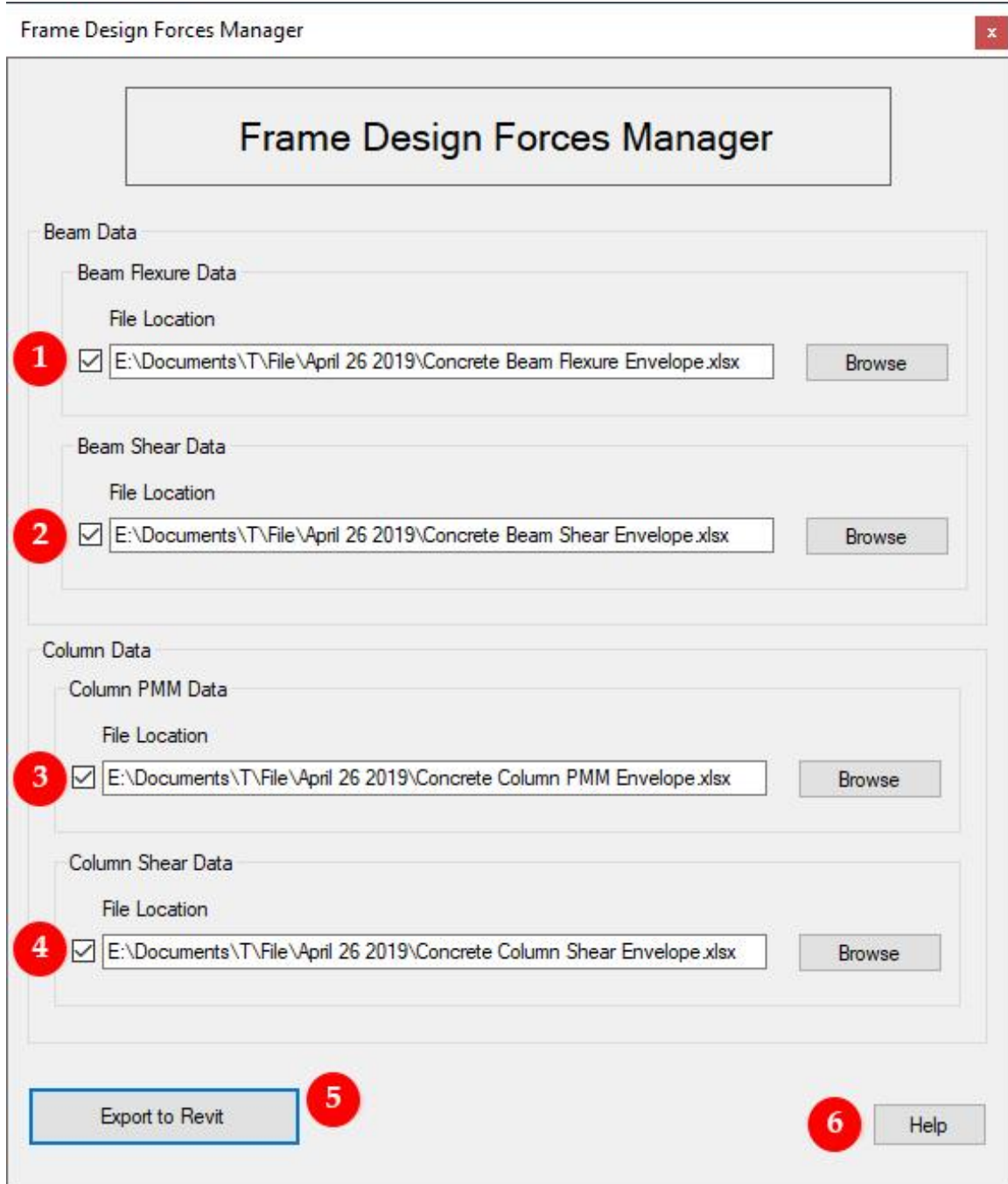


Figure 52: Frame Design Forces Manager tool GUI

## 5.4 Developing SAFE Tools for BIM Implementation

Unlike Revit and ETABS, SAFE 2016 does not come with an API (application programming interface) that give access to its core. Neither a plugin nor an external tool can be programmed to extract information directly from SAFE. Thus, for this thesis, an indirect way was used to extract important data from SAFE. Like ETABS, SAFE allows outputs to be exported in MS Access files. A tool was created to read and extract important data from these output files.

### Foundation Analysis and Design Manager tool

The flowchart of this tool can be seen on Figure 53. It begins by locating the SAFE output files, which have to be provided by the user<sup>10</sup>. After retrieving the data from the output files, the tool will check whether the provide data is the required one. Then, the data is organized and displayed. Finally, the data extracted from SAFE is exported in SBIM file format.

Figure 54 presents the graphic user interface of the foundation design manager tool. Area 1 is where the file location of the SAFE output file needed to be provided. Regarding design data, the same issue that was faced by the “Slab Analysis and Design Manager” tool is also faced here. Hence, rebar area requirements are manually provided by the engineer.

Area 3 is where the typical bar diameter and spacing are provided by the engineer. A rebar diameter set can be provided and it will be used by the tool as discussed before. These values will be used to populate the foundation design table (Area 6). This table is then manually modified by the engineer. Same with the slab analysis and design tool, here also the engineer may enter the required rebar area or rebar spacing. Whichever one is provided; the tool will compute the other one.

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<sup>10</sup> Once the user provides the file location, the tool will save the location. Next time the tool is run; the user does not need to provide the location since the tool will remember it.

At Area 5, a “Help” button is provided to assist in identifying what output files are required from SAFE. The “Units” button at the same area will provide the units of the parameters displayed on the table.

Soil pressure, displacement, forces, stress and punching shear design results are also retrieved by the tool. At Area 2, the engineer will select from the list of the load combinations used for foundation analysis and the tool will filter out the above analysis and design result for the specified load combination. Finally, by pressing the “Export to Revit” button (Area 4), all analysis and design data is exported to Revit through SBIM file.

The list of important codes from the source code of the SAFE tool is given on Appendix B Table 11.

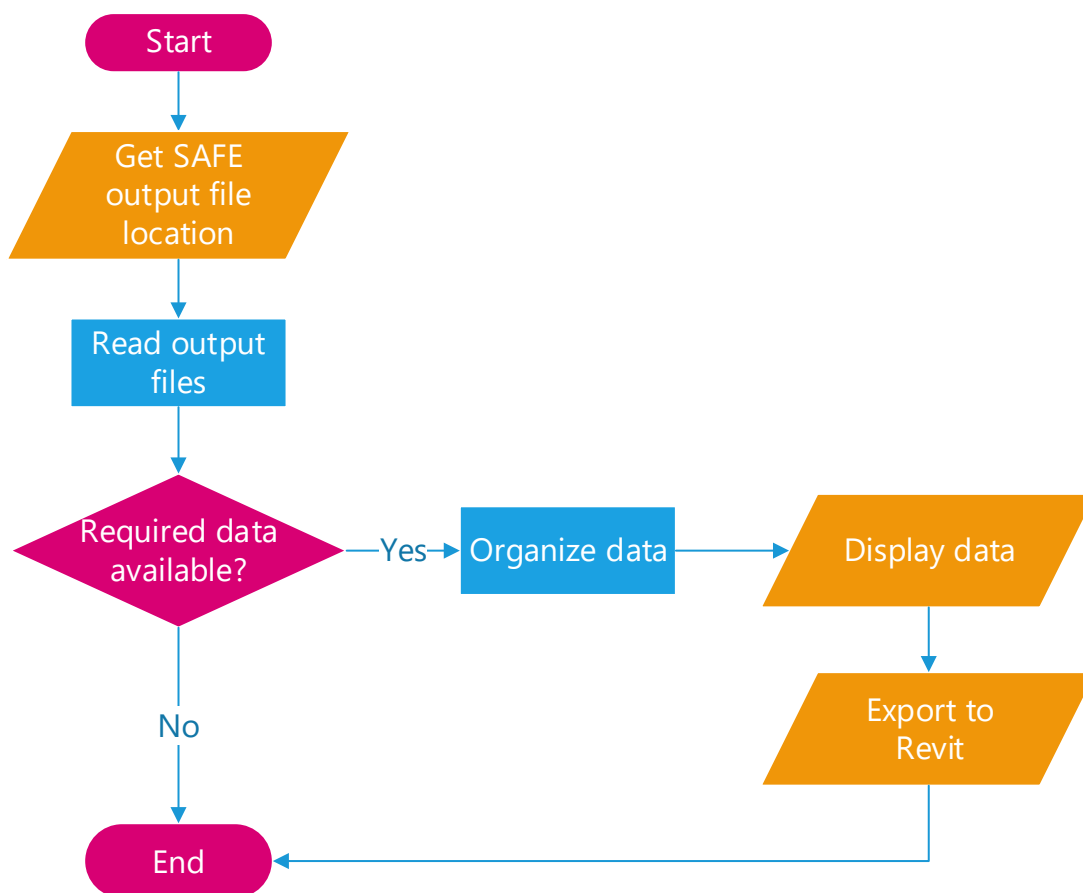


Figure 53: Foundation analysis and design manager tool flowchart

Foundation Analysis and Design Manager

Input File **1**

File Location  
E:\Documents\Thesis\G +12 MIXED USE SAFE.mdb

Load Combination for  
Soil Pressure FACTORED **2** Forces and Stress FACTORED  
Displacements FACTORED Punching Shear FACTORED

Rebar Parameters  
Minimum Diameter 20 **3**  
Maximum Spacing 200  
Minimum Spacing 100  
Spacing Round off 20 **4**

Click To  
Export To Revit  
Reanalyze  
Load

Help **5** Units

Foundation Reinforcement Data

Unique Name	Tag	Thickness	As Top (X)	Bar Dia Top (X)	Bar Spacing Top (X)	As Bot (X)	Bar Dia Bot (X)	Bar Spacing Bot (X)	As Top (Y)	Bar Dia Top (Y)	Bar Spacing Top (Y)	As Bot (Y)	Bar Dia Bot (Y)	Bar Spacing Bot (Y)
339610	F-1	1000	1670	20	180	1571	20	200	1571	20	200	1571	20	200
339641	F-2	1200	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339683	F-3	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339693	F-4	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339725	F-5	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339757	F-6	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339789	F-7	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339821	F-8	1200	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339829	F-9	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339960	F-10	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
339992	F-11	1200	1571	20	200	1571	20	200	1571	20	200	1571	20	200
340022	F-12	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200
340054	F-13	1200	1571	20	200	1571	20	200	1571	20	200	1571	20	200
340086	F-14	1000	1571	20	200	1571	20	200	1571	20	200	1571	20	200

**6**

Figure 54: Foundation Analysis and Design Manager tool GUI

## 5.5 Developing Revit Plugin for BIM Implementation

Developing plugin for Revit is harder and more laborious than doing the same for ETABS. This stems from the fact that Revit's API cannot be accessed by external application. Only in-process plugins are run in Revit. This leads to a more strenuous programming experience as compared to ETABS.

To debug a Revit plugin, Revit needs to be run anew by the debugger. However, Revit takes a good amount of time to open depending on the computer capacity. The situation is further exasperated by the fact that to continue working on the codes, Revit needs to be closed. Thus, the next time the code is debugged, Revit needs to be launched all over again. Since the codes are continuously being debugged, significantly large amount of time is wasted by simply waiting for Revit to launch.

Due to the condition elaborated above, coding of Revit plugin is kept to the minimum necessary. Most part of the interoperability is handled by the tools on the ETABS side. The function of the Revit plugin is limited to receiving data from the ETABS tools and store it in the central model.

### **Import Data tool**

A single Revit plugin, titled "Import Data", was program to perform all the required tasks in Revit end of the data exchange. This plugin is able to communicate with all the ETABS plugins and tools as well as the SAFE tool.

Figure 55 presents the flowchart of the tool. Its task begins by locating and reading seven structural BIM (\*. SBIM) files containing story data, wall analysis and design data, beam design data, column design data, slab analysis design data, foundation analysis and design data and frame design forces data. These SBIM files are the once created by the ETABS plugins and the SAFE tool. The Revit plugin will unload the content of these output files. The data on these files is well organized so no organization is required.

All available data of a structural object is grouped with its unique id. Hence, each object is called by the Revit plugin one by one using its unique id and receives all associated data.

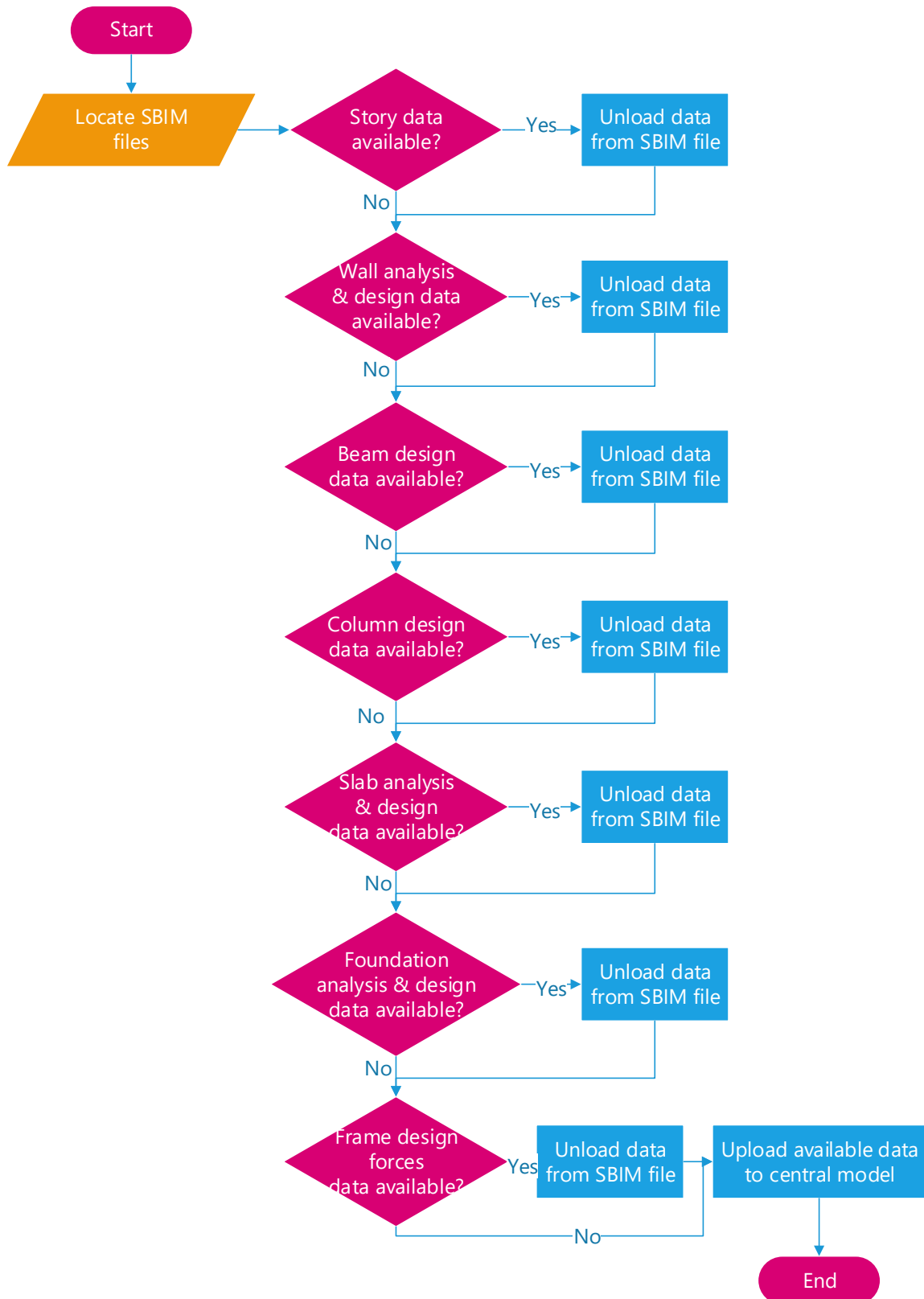


Figure 55: Import Data tool flowchart

Figure 56 displays the graphic user interface (GUI) of the plugin. When the “Import data” plugin is run from Revit commands, the tool will display this GUI. On this interface, the plugin asks for seven SBIM file locations (Area 1 - 7). The user is not required to provide the location of each SBIM file. Rather, when file location of one SBIM file is provided, the plugin will automatically look for the rest of the SBIM files in that file location. The plugin will permanently save the file location, thus when the plugin is run again, it will remember the file location of the SBIM files and automatically read them.

If one or more SBIM file is provided, the “Ok” button can be pressed to proceed. Then, the plugin will unload the data found in the file or files. Using the unique id of objects and label of levels, the unloaded data is loaded into the central model.

The list of important codes from the source code of the Revit plugin is given on Appendix B Table 12.

The loading of structural data into the central model not only concludes the function of this particular plugin but also the function of all the ETABS and SAFE tools developed this far. Their main purpose was to transfer important structural analysis and design data from the design tools and from their own computation to the central model in Revit. This was finalized by the “Import data” plugin solving the interoperability issue and achieving the adoption of BIM.

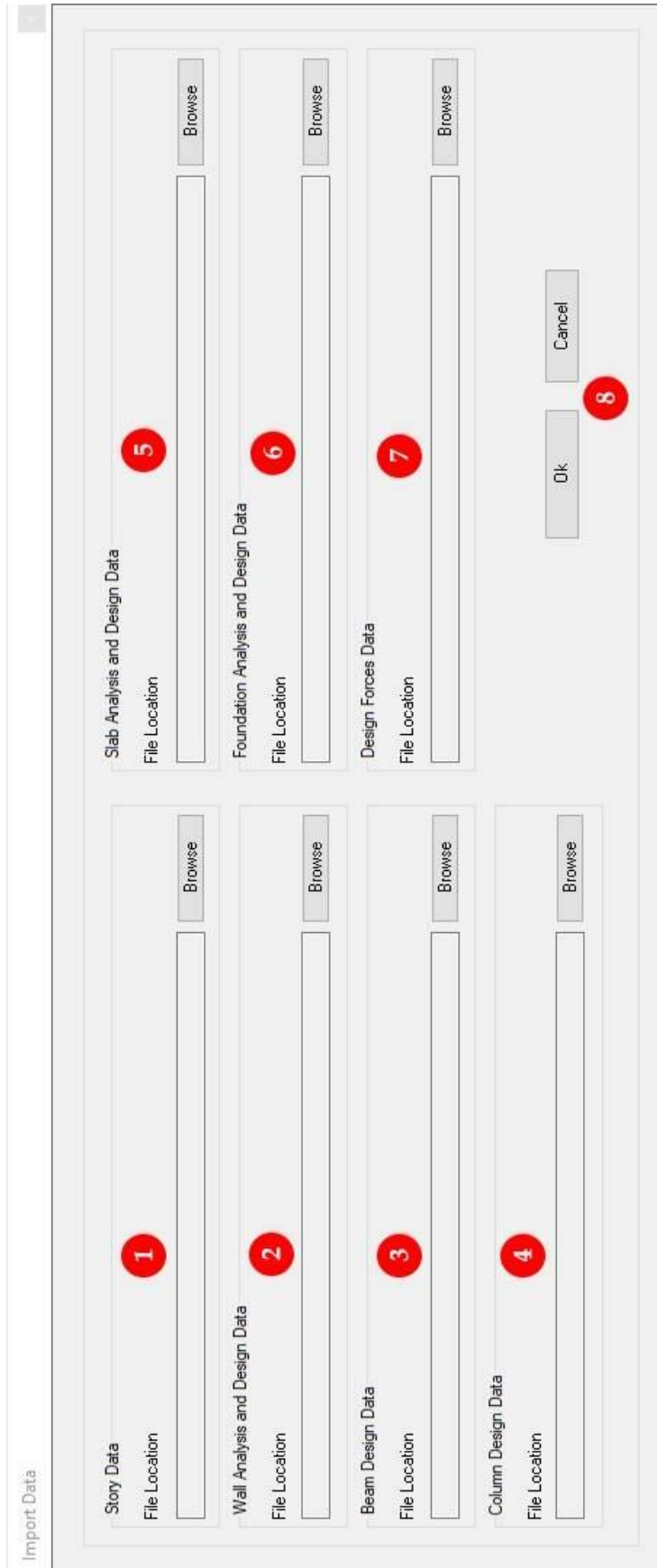


Figure 56: Import Data GUI

## CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

During the research, a BIM workflow was implemented on the structural design phase of a sample building project. BIM was involved in every phase of the structural design. Preparing the structural model, analysis, design, verifications, preparation of construction detailing and clash detecting were all aided by BIM.

Drawing out the structural model from the architectural model proved to be more advantageous than creating it anew. The structural model was created far more quickly and it perfectly captured the essences and complexity of the architectural model. Same is true for preparation of construction detail drawings. Instead of creating the drawings anew, they were added to the existing central model. Thus, large amount of rework was avoided.

Existing structural object in Revit do not have the capacity to store structural analysis and design results. Hence, objects that are capable of storing such information were created. This information was created on structural analysis packages ETABS and SAFE. The interoperability of these packages with Revit was expanded to include the migration of structural analysis and design results by developing tools and plugins.

Structural engineering and architecture disciplines were connected together through a common database or central model. The developed plugins played a vital role in this integration. There is no longer a data island where both disciplines store data separately. Collaboration and communication are much more efficient due to the common database.

Furthermore, the tools and plugins developed served to integrate fragmented structural design tasks. Computations that are not performed by ETABS are introduced to ETABS through the plugins. The result of those plugins, similar with the result of ETABS analysis and design, is stored in the central model. At the end, the central model was rich with structural data.

By joining the final structural model with the architectural model, the real-world interaction of those disciplines was realized digitally. As a result, numerous clashes between those two disciplines were detected and dealt with. The preemptive detection and resolution of these clashes at this stage will circumvent costly abortive works in later stages of the building project.

The structural object families and the various structural analysis & design parameters created during this thesis can be reused in future building project, with or without modification, to implement BIM workflow. Likewise, the tools and plugins developed during this thesis can be reused in other building project.

While the BIM workflow presented in this thesis was geared towards structural engineering, the techniques followed can be adopted for the integration of other disciplines such as sanitary engineering and electrical engineering.

## **6.2 Recommendations**

The thesis focused on the integration of structural engineering work with architectural work using a central model. To harness the full benefits of BIM integration during the design phase of a building project, other involved disciplines should also connect their work with the central model. More research should be carried out to layout the workflow of such integration.

For a design team member to successfully adopt BIM, the members need to be aware of the other members' work. It is difficult to create cross discipline cooperation if the involved individuals lack cross discipline knowledge. Thus, engineering students as well as professionals should improve their cross-discipline knowledge of the other related discipline.

While the scope of the thesis was BIM implementation during the structural design of a building project, the BIM workflow goes well beyond that. Construction planning, construction and facility management can all be improved by BIM adoption. Large amount of information is created during these phases and a number of software packages are used. How this information can be integrated with the rest of the building projects' information and how the software packages can be integrated with each other so as to function as a single platform need to be investigated and determined. Integrating the important task of bar curtailing within the BIM process will save large amount of money and it should be investigated.

To implement BIM, it is necessary to have owners care about it. To achieve this, the benefit BIM garners for clients should be laid out for them. The business side of BIM and the organizational requirements necessary for its implementation are also possible areas of investigation. The legal and contractual effects of BIM implementation should also be explored.

As it was evident from the review of BIM experience of some countries, government incentives and support play a role in increasing nationwide BIM uptake. Since BIM's popularity is surging across the globe, the Ethiopian government should look into ways to introduce and encourage BIM uptake in the country's design and construction industry.

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## APPENDIX A: Revit Structural Families and their Parameters

The Revit families representing structural objects do not have parameters to store structural analysis and design information. Hence, in the research, such parameters were created and added to the structural families. Some of the parameters were created along with the respective family while other were created and added to existing system families. These structural objects and their families are discussed on section 3.6.

From Table 3 - Table 9 presents the structural analysis and design parameters created and added to structural families so that they can store such information.

**Table 3: Parameters created for project information system family**

Parameter
Structural type
Ductility class
Seismic zone
Bedrock acceleration ratio
Spectrum type
Ground type
Behavior factor, q
Importance class
Importance factor
Correction factor
Regularity in elevation
Regularity in plan
Fundamental period of vibration
Recommended foundation type
Recommended foundation depth
Allowable bearing capacity (kPa)
Soil formation
Recommended foundation type (Alt)
Recommended foundation depth (Alt)
Allowable bearing capacity (kPa) (Alt)
Soil formation (Alt)

**Table 4: RC Beam family parameters**

Parameter	Unit	Parameter	Unit
(+) Moment (End-I)	kN-m	Bar Diameter J – Top (Support)	mm
(+) Moment (Middle)	kN-m	Required No. of Bars J – Top (Support)	
(+) Moment (End-J)	kN-m	Provided No. of Bars J – Top (Support)	
(+) Moment Combo (End-I)	-	Bar Diameter I – Bottom	mm
(+) Moment Combo (Middle)	-	Required No. of Bars I – Bottom	
(+) Moment Combo (End-J)	-	Provided No. of Bars I – Bottom	
(-) Moment (End-I)	kN-m	Bar Diameter M – Bottom	mm
(-) Moment (Middle)	kN-m	Required No. of Bars M – Bottom	
(-) Moment (End-J)	kN-m	Provided No. of Bars M – Bottom	
(-) Moment Combo (End-I)	-	Shear Steel-I	mm <sup>2</sup> /m
(-) Moment Combo (Middle)	-	Shear Steel-M	mm <sup>2</sup> /m
(-) Moment Combo (End-J)	-	Shear Steel-J	mm <sup>2</sup> /m
Shear Force (End-I)	kN	Torsion Long. Steel-I	mm <sup>2</sup>
Shear Force (Middle)	kN	Torsion Long. Steel-M	mm <sup>2</sup>
Shear Force (End-J)	kN	Torsion Long. Steel-J	mm <sup>2</sup>
Shear Combo (End-I)		Torsion Trans. Steel-I	mm <sup>2</sup> /m
Shear Combo (Middle)		Torsion Trans. Steel-M	mm <sup>2</sup> /m
Shear Combo (End-J)		Torsion Trans. Steel-J	mm <sup>2</sup> /m
Torsion (End-I)	kN-m	Shear Plus Torsion Steel-I	mm <sup>2</sup> /m
Torsion (Middle)	kN-m	Shear Plus Torsion Steel-M	mm <sup>2</sup> /m
Torsion (End-J)	kN-m	Shear Plus Torsion Steel-J	mm <sup>2</sup> /m
Torsion Combo (End-I)		Bar Diameter J – Bottom	mm
Torsion Combo (Middle)		Required No. of Bars J – Bottom	
Torsion Combo (End-J)		Provided No. of Bars J – Bottom	
Top Steel-I	mm <sup>2</sup>	Stirrup Diameter - I	mm
Top Steel-M	mm <sup>2</sup>	Required Stirrup Spacing - I	mm
Top Steel-J	mm <sup>2</sup>	Provided Stirrup Spacing - I	mm
Bottom Steel-I	mm <sup>2</sup>	Stirrup Diameter – M	mm
Bottom Steel-M	mm <sup>2</sup>	Required Stirrup Spacing – M	mm
Bottom Steel-J	mm <sup>2</sup>	Provided Stirrup Spacing – M	mm
Bar Diameter – Top	mm	Stirrup Diameter – J	mm
Required No. of Bars - Top		Required Stirrup Spacing – J	mm
Provided No. of Bars - Top		Provided Stirrup Spacing – J	mm
Bar Diameter I – Top (Support)	mm		
Required No. of Bars I – Top (Support)			
Provided No. of Bars I – Top (Support)			

**Table 5: RC Column family parameters**

Parameter	Unit	Parameter	Unit
Axial Force (Top)	kN	Longitudinal Steel	mm <sup>2</sup>
Moment Major (Top)	kN-m	Longitudinal Bar Diameter	mm
Moment Minor (Top)	kN-m	Required No. Longitudinal Bar	-
PMM Combo (Top)	-	Provided No. Longitudinal Bar	-
PMM Ratio/ Rebar% (Top)	-	Major Shear Reinforcement	mm <sup>2</sup> /m
Axial Force (Bottom)	kN	Minor Shear Reinforcement	mm <sup>2</sup> /m
Moment Major (Bottom)	kN-m	Transversal Bar Diameter	mm
Moment Minor (Bottom)	kN-m	Required Transversal Bar Spacing	mm
PMM Combo (Bottom)	-	Provided Transversal Bar Spacing	mm
PMM Ratio/ Rebar% (Bottom)	-	Group Name	-
Shear Major (Top)	kN		
Shear Major Combo (Top)	-		
Shear Minor (Top)	kN		
Shear Minor Combo (Top)	-		
Shear Major (Bottom)	kN		
Shear Major Combo (Bottom)	-		
Shear Minor (Bottom)	kN		
Shear Minor Combo (Bottom)	-		
Error/Warning			

**Table 6: Parameters created for wall system family**

Parameter	Unit	Parameter	Unit
Top Design Moment -Left (Spandrel)	kN-m	Trans. As	mm <sup>2</sup> /m
Top Rebar As -Left (Spandrel)	mm <sup>2</sup>	Trans. Bar Diameter	mm
Top Rebar Ratio-Left (Spandrel)		Trans. Required Spacing	mm
Top Rebar Combo -Left (Spandrel)		Trans. Provided Spacing	mm
Bottom Design Moment -Left (Spandrel)	kN-m	Errors/ Warning	
Bottom Rebar As -Left (Spandrel)	mm <sup>2</sup>	Normalized Compressive Stress (Pier)	MPa
Bottom Rebar Ratio-Left (Spandrel)		Normalized Compressive Limit (Pier)	MPa
Bottom Rebar Combo -Left (Spandrel)		F11	kN/m
Top Design Moment -Right (Spandrel)	kN-m	F22	kN/m
Top Rebar As -Right (Spandrel)	mm <sup>2</sup>	F12	kN/m
Top Rebar Ratio -Right (Spandrel)		F Max	kN/m
Top Rebar Combo -Right (Spandrel)		F Min	kN/m
Top Rebar Diameter (Spandrel)		FVM	kN/m
Top Rebar Required No. (Spandrel)		M11	kN-m/m
Top Rebar Provided No. (Spandrel)		M22	kN-m/m
Bottom Design Moment -Right (Spandrel)	kN-m	M12	kN-m/m
Bottom Rebar As -Right (Spandrel)	mm <sup>2</sup>	M Max	kN-m/m
Bottom Rebar Ratio -Right (Spandrel)		M Min	kN-m/m
Bottom Rebar Combo -Right (Spandrel)		V13	kN/m
Bottom Rebar Diameter (Spandrel)	mm	V23	kN/m
Bottom Rebar Required No. (Spandrel)		V Max	kN/m
Bottom Rebar Provided No.		S11 (Top)	MPa

Application of BIM using Revit and Other Conventional Structural Design Software: A  
Case Study on a High-Rise Building

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(Spandrel)			
Design V. Shear Force –Left (Spandrel)	kN	S22 (Top)	MPa
V. Shear Rebar Combo –Left (Spandrel)		S12 (Top)	MPa
V. Shear Rebar Av –Left (Spandrel)	mm <sup>2</sup> /m	S Max (Top)	MPa
V. Shear Rebar Diameter –Left (Spandrel)	mm	S Min (Top)	MPa
V. Shear Rebar Required Spacing -Left (Spandrel)	mm	SVM (Top)	MPa
V. Shear Rebar Provided Spacing -Left (Spandrel)	mm	S11 (Bottom)	MPa
Design V. Shear Force –Right (Spandrel)	kN	S22 (Bottom)	MPa
V. Shear Rebar Combo – Right (Spandrel)		S12 (Bottom)	MPa
V. Shear Rebar Av – Right (Spandrel)	mm <sup>2</sup> /m	S Max (Bottom)	MPa
V. Shear Rebar Diameter – Right (Spandrel)	mm	S Min (Bottom)	MPa
V. Shear Rebar Required Spacing - Right (Spandrel)	mm	SVM (Bottom)	MPa
V. Shear Rebar Provided Spacing - Right (Spandrel)	mm	S13 Avg	MPa
Required Reinforcement % (Uniform Reinforcing)		S23 Avg	MPa
Long. As (Uniform Reinforcing)	mm <sup>2</sup>	SMax Avg	MPa
Long. Bar Diameter (Uniform Reinforcing)	mm	E11 (Top)	mm/mm
Long. Required Spacing (Uniform Reinforcing)	mm	E22 (Top)	mm/mm
Long. Provided Spacing (Uniform Reinforcing)	mm	G12 (Top)	mm/mm
Provided Reinforcement % (Uniform Reinforcing)		E Max (Top)	mm/mm
Edge Member Length –Left (Simplified T & C)	mm	E Min (Top)	mm/mm
Edge Member Length –Right (Simplified T & C)	mm	EVM (Top)	mm/mm
As -Left (Simplified T & C)	mm <sup>2</sup>	E11 (Bottom)	mm/mm
Bar Diameter -Left (Simplified T & C)	mm	E22 (Bottom)	mm/mm
Required No. of Bar -Left	mm	G12 (Bottom)	mm/mm

Application of BIM using Revit and Other Conventional Structural Design Software: A  
Case Study on a High-Rise Building

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(Simplified T & C)			
Provided No. of Bar -Left (Simplified T & C)	mm	E Max (Bottom)	mm/mm
As -Right (Simplified T & C)	mm <sup>2</sup>	E Min (Bottom)	mm/mm
Bar Diameter - Right (Simplified T & C)	mm	EVM (Bottom)	mm/mm
Required No. of Bar - Right (Simplified T & C)	mm	G13 Avg	mm/mm
Provided No. of Bar - Right (Simplified T & C)	mm	G23 Avg	mm/mm
		GMax Avg	mm/mm

**Table 7: Parameters created for floor(slab) system family**

Parameter	Unit	Parameter	Unit
M11	kN-m/m	G12 (Bottom)	mm/mm
M22	kN-m/m	E Max (Bottom)	mm/mm
M12	kN-m/m	E Min (Bottom)	mm/mm
M Max	kN-m/m	EVM (Bottom)	mm/mm
M Min	kN-m/m	G13 Avg	mm/mm
V13	kN/m	G23 Avg	mm/mm
V23	kN/m	GMax Avg	mm/mm
V Max	kN/m	As - Sup. N.	mm <sup>2</sup> /m
S11 (Top)	MPa	As - Sup. E.	mm <sup>2</sup> /m
S22 (Top)	MPa	As - Sup. S.	mm <sup>2</sup> /m
S12 (Top)	MPa	As - Sup. W.	mm <sup>2</sup> /m
S Max (Top)	MPa	Rebar Diameter - Sup. N.	mm
S Min (Top)	MPa	Rebar Spacing - Sup. N.	mm
SVM (Top)	MPa	Rebar Diameter - Sup. E.	mm
S11 (Bottom)	MPa	Rebar Spacing - Sup. E.	mm
S22 (Bottom)	MPa	Rebar Diameter - Sup. S.	mm
S12 (Bottom)	MPa	Rebar Spacing - Sup. S.	mm
S Max (Bottom)	MPa	Rebar Diameter - Sup. W.	mm
S Min (Bottom)	MPa	Rebar Spacing - Sup. W.	mm
SVM (Bottom)	MPa	Rebar Diameter - Fie. X	mm
S13 Avg	MPa	Rebar Spacing - Fie. X	mm
S23 Avg	MPa	As - Fie. X	mm <sup>2</sup> /m
SMax Avg	MPa	As - Fie. Y	mm <sup>2</sup> /m
E11 (Top)	mm/mm	Rebar Diameter - Fie. Y	mm
E22 (Top)	mm/mm	Rebar Spacing - Fie. Y	mm
G12 (Top)	mm/mm	Rebar Diameter - Bottom (X)	mm
E Max (Top)	mm/mm	Rebar Spacing - Bottom (X)	mm
E Min (Top)	mm/mm	Rebar Diameter - Bottom (Y)	mm
EVM (Top)	mm/mm	Rebar Spacing - Bottom (Y)	mm
E11 (Bottom)	mm/mm		
E22 (Bottom)	mm/mm		

**Table 8: Parameters created for foundation slab system family**

Parameter	Unit	Parameter	Unit
Maximum Soil Pressure	MPa	S Max (Top)	MPa
Minimum Soil Pressure	MPa	S Min (Top)	MPa
Displacement X	mm	SVM (Top)	MPa
Displacement Y	mm	S11 (Mid)	MPa
Displacement Z	mm	S22 (Mid)	MPa
Rotation X	Rad	S12 (Mid)	MPa
Rotation Y	Rad	S Max (Mid)	MPa
Rotation Z	Rad	S Min (Mid)	MPa
Shear Force	kN	SVM (Mid)	MPa
Shear Stress Capacity	kN	S11 (Bottom)	MPa
Maximum Shear Stress	MPa	S22 (Bottom)	MPa
Punching Shear Ratio	-	S12 (Bottom)	MPa
Punching Shear Status	-	S Max (Bottom)	MPa
Major Axis Moment	kN-m	S Min (Bottom)	MPa
Minor Axis Moment	kN-m	SVM (Bottom)	MPa
F11	kN/m	S13 Avg	MPa
F22	kN/m	S23 Avg	MPa
F12	kN/m	SMax Avg	MPa
F Max	kN/m	Foundation Tag	-
F Min	kN/m	As - Top (X)	mm <sup>2</sup> /m
FVM	kN/m	As - Bottom (X)	mm <sup>2</sup> /m
M11	kN-m/m	As - Top (Y)	mm <sup>2</sup> /m
M22	kN-m/m	As - Bottom (Y)	mm <sup>2</sup> /m
M12	kN-m/m	Rebar Diameter - Top (X)	mm
M Max	kN-m/m	Rebar Spacing - Top (X)	mm
M Min	kN-m/m	Rebar Diameter - Top (Y)	mm
V13	kN/m	Rebar Spacing - Top (Y)	mm
V23	kN/m	Rebar Diameter - Bottom (X)	mm
V Max	kN/m	Rebar Spacing - Bottom (X)	mm
S11 (Top)	MPa	Rebar Diameter - Bottom (Y)	mm
S22 (Top)	MPa	Rebar Spacing - Bottom (Y)	mm
S12 (Top)	MPa		

**Table 9: Parameters created for story system family**

Parameter	Unit	Parameter	Unit
Mass	Kg	Max. Displacement X	mm
Cumulative Mass	Kg	Max. Displacement Y	mm
XCM	mm	Diaphragm Displacement X	mm
YCM	mm	Diaphragm Displacement Y	mm
XCCM	mm	Avg. Drift X	mm
YCCM	mm	Avg. Drift Y	mm
XCR	mm	Max. Drift X	mm
YCR	mm	Max. Drift Y	mm
UX	m/s <sup>2</sup>	Drift/H X	-
UY	m/s <sup>2</sup>	Drift/H Y	-
UZ	m/s <sup>2</sup>	Inter-story Drift (X)	-
P Top	kN	Inter-story Drift (Y)	-
MX Top	kN-m	Θ(X)	-
MY Top	kN-m	Θ(Y)	-
P Bottom	kN	Slenderness	-
MX Bottom	kN-m	Structural Eccentricity X	mm
MY Bottom	kN-m	Structural Eccentricity Y	mm
VX	kN	Torsional Radius X	mm
VY	kN	Torsional Radius Y	mm
T	kN-m	Rotation about Z	rad
Shear X	kN	Torsional Stiffness	kNm/rad
Shear Y	kN	Radius of gyration	m
Stiffness X	kN/m	Stiffness X Variation	%
Stiffness Y	kN/m	Stiffness Y Variation	%
Avg. Displacement X	mm	Mass Variation	%
Avg. Displacement Y	mm		

## **APPENDIX B: LIST OF IMPORTANT PROGRAMMING CODES**

For the research, nine tools were programmed. While seven of these tools were developed for ETABS, the other two were for SAFE and Revit (one tool for each). The tools and their development are discussed on section 5.3, 5.4 and 5.5.

Providing the source code for all the tools will take a large amount of space. Instead, codes and code blocks which were used repeatedly and carried out the main function of the tools are provided. Table 10 provides important codes from those tools that carry out their task by directly connecting to an ETABS model. Table 11 lists the central codes used by tools that used ETABS and SAFE output files to perform their task. And the last table, Table 12, presents chief codes form the source code of the Revit plugin.

**Table 10: Code from ETABS plugin source codes: Direct ETABS access**

<b>Code</b>	<pre>myETABSObject = (ETABSV17.COAPI)System.Runtime.InteropServices.Marshal. GetActiveObject("CSI.ETABS.API.ETABSObject");  myModel = myETABSObject.SapModel;</pre>
<b>Description</b>	Access an open ETABS model
<b>Code</b>	<pre>ret = myModel.Story.GetNameList(ref NumberOfStories, ref StoryNames);</pre>
<b>Description</b>	Retrieves the names of all defined stories in the structure.
<b>Code</b>	<pre>ret = myModel.Story.GetStories(ref NumberStories, ref StoryListedNames, ref StoryElevations, ref StoryHeights, ref IsMasterStory, ref SimilarToStory, ref SpliceAbove, ref SpliceHeight);</pre>
<b>Description</b>	Retrieves all stories and information associated with them.
<b>Code</b>	<pre>ret = myModel.PropMaterial.GetNameList(ref NumberOfMaterials, ref MaterialNameList, MatType);</pre>
<b>Description</b>	Retrieves the names of all defined material properties of the specified type.
<b>Code</b>	<pre>ret = myModel.FrameObj.GetAllFrames(ref NumberNames, ref FrameName, ref PropName, ref StoryName, ref PointName1, ref PointName2, ref Point1X, ref Point1Y, ref Point1Z, ref Point2X, ref Point2Y, ref Point2Z, ref Angle, ref Offset1X, ref Offset2X, ref Offset1Y, ref Offset2Y, ref Offset1Z, ref Offset2Z, ref CardinalPoint, csys);</pre>
<b>Description</b>	Retrieves all frame objects and their associated data
<b>Code</b>	<pre>ret = myModel.FrameObj.GetLabelFromName(FrameNames, ref BeamPerGroupLabelName, ref StoryList);</pre>
<b>Description</b>	Retrieves the label and story of a frame object identified by its unique name
<b>Code</b>	<pre>ret = myModel.PropFrame.GetAllFrameProperties(ref NumberOfSections, ref SectionName, ref PropType, ref t3, ref t2, ref tf, ref tw, ref t2b, ref tfb);</pre>
<b>Description</b>	Retrieves all frame properties defined in the ETABS model along their associated data.
<b>Code</b>	<pre>ret = myModel.PropFrame.GetTypeRebar(FrameNames, ref FrameType);</pre>
<b>Description</b>	Retrieves the rebar design type for the specified frame section property
<b>Code</b>	<pre>ret = myModel.PropFrame.GetMaterial(FrameSectionName, ref MaterialName);</pre>
<b>Description</b>	Retrieves material property data for a specified frame section property.
<b>Code</b>	<pre>ret = myModel.PropFrame.GetRebarColumn(FrameSectionName, ref MatPropLong, ref MatPropConfine, ref Pattern, ref ConfineType, ref Cover, ref NumberCBars, ref NumberR3Bars, ref NumberR2Bars, ref RebarSize, ref TieSize, ref TieSpacingLongit, ref Number2DirTieBars, ref Number3DirTieBars, ref ToBeDesigned);</pre>
<b>Description</b>	Retrieves rebar data for specified column frame section.

Application of BIM using Revit and Other Conventional Structural Design Software: A Case Study on a High-Rise Building

<b>Code</b>	<code>ret = myModel.PropFrame.GetRectangle(FrameSectionName, ref FileName, ref MatProp, ref T3, ref T2, ref Color, ref Notes, ref GUID);</code>
<b>Description</b>	Retrieves frame section property data for a specified rectangular frame section.
<b>Code</b>	<code>ret = myModel.PropFrame.GetModifiers(FrameSectionName, ref Modifiers);</code>
<b>Description</b>	Retrieves the modifier assignments for a specified frame section property
<b>Code</b>	<code>ret = myModel.PropFrame.SetRectangle(FrameSectionName, MatProp, SectionDepth, SectionWidth, -1, "", "");</code>
<b>Description</b>	Initializes a solid rectangular frame section property.
<b>Code</b>	<code>ret = myModel.PropFrame.SetRebarBeam(FrameSectionName, MatPropLong, BarMatProp, ConcCoverTop, ConcCoverBottom, 0, 0, 0, 0);</code>
<b>Description</b>	Assigns beam rebar data to a beam frame sections
<b>Code</b>	<code>ret = myModel.PropFrame.SetModifiers(FrameSectionName, ref Modifiers);</code>
<b>Description</b>	Sets the frame modifier assignment for a specified frame objects.
<b>Code</b>	<code>ret = myModel.Func.GetNameList(ref NumberFunc, ref FuncName, FuncType);</code>
<b>Description</b>	Retrieves the defined response spectrum and time history functions.
<b>Code</b>	<code>ret = myModel.LoadCases.ResponseSpectrum.SetCase(LoadCaseNameList);</code>
<b>Description</b>	Initializes a response spectrum load case.
<b>Code</b>	<code>ret = myModel.LoadCases.ResponseSpectrum.SetLoads(LoadCaseName, NumberLoadName, ref LoadName, ref Func, ref SF, ref CsysD, ref Angle);</code>
<b>Description</b>	Assign loads and their scale factor to a specified response spectrum load case.
<b>Code</b>	<code>ret = myModel.LoadCases.ResponseSpectrum.GetLoads(ResponseSpectrumLoadCases, ref NumberOfLoadCase, ref LoadName, ref Func, ref SF, ref CsysD, ref Angle);</code>
<b>Description</b>	Retrieves the load names and their associated data for a response spectrum load case.
<b>Code</b>	<code>ret = myModel.LoadCases.ModalEigen.SetCase(LoadCaseName);</code>
<b>Description</b>	Initializes a modal eigen load case.
<b>Code</b>	<code>ret = myModel.LoadCases.GetNameList(ref NumberOfLoadCase, ref LoadCaseName, CaseType);</code>
<b>Description</b>	Retrieves the names of all defined load cases of the specified type.
<b>Code</b>	<code>ret = myModel.LoadPatterns.GetNameList(ref NumberOfLoadPattern, ref PatternName);</code>
<b>Description</b>	Retrieves the names of all defined load patterns.
<b>Code</b>	<code>ret = myModel.LoadPatterns.GetLoadType(PatternName, ref LoadPatternType);</code>

Application of BIM using Revit and Other Conventional Structural Design Software: A Case Study on a High-Rise Building

<b>Description</b>	Retrieves the load type for a specified load pattern
<b>Code</b>	<code>ret = myModel.LoadPatterns.Add(LoadPatternNames, SelectedLoadType, LoadPatterntSelfWeightMultiplier, true);</code>
<b>Description</b>	Adds a new load pattern.
<b>Code</b>	<code>ret = myModel.RespCombo.Add(LoadComboName, 0);</code>
<b>Description</b>	Adds a new load combination.
<b>Code</b>	<code>ret = myModel.RespCombo.SetCaseList(LoadComboName, ref ComboType, LoadPatterns, 1);</code>
<b>Description</b>	Adds (or modifies) a specified load case or combination in a specified load combination.
<b>Code</b>	<code>ret = myModel.RespCombo.GetNameList(ref NumberOfCombo, ref ComboName);</code>
<b>Description</b>	Retrieves the names of all defined load combinations.
<b>Code</b>	<code>ret = myModel.GroupDef.GetNameList(ref NumberGroups, ref GroupNameList);</code>
<b>Description</b>	Retrieves the name of all the groups.
<b>Code</b>	<code>ret = myModel.GroupDef.SetGroup_1(GroupName, -1);</code>
<b>Description</b>	Creates a group.
<b>Code</b>	<code>ret = myModel.FrameObj.SetGroupAssign("", GroupName, false, SelectedFrames);</code>
<b>Description</b>	Adds or removes frame objects from a specified group
<b>Code</b>	<code>ret = myModel.GroupDef.GetAssignments(GroupName, ref NumberItems, ref ObjectType, ref ObjectName);</code>
<b>Description</b>	Retrieves the objects assigned to a specified group
<b>Code</b>	<code>ret = myModel.Results.Setup.SetCaseSelectedForOutput(ResponseSpectrumLoadCases);</code>
<b>Description</b>	Sets a load case for outputs.
<b>Code</b>	<code>ret = myModel.Results.BaseReact(ref NumberResults, ref LoadCase, ref StepType, ref StepNum, ref FX, ref FY, ref FZ, ref MX, ref ParamMy, ref MZ, ref GX, ref GY, ref GZ);</code>
<b>Description</b>	Reports the structure total base reactions for the specified load case.
<b>Code</b>	<code>ret = myModel.Results.ModalParticipatingMassRatios(ref NumberOfModel, ref ModalLoadCase, ref StepType, ref StepNum, ref Period, ref UX, ref UY, ref UZ, ref SumUX, ref SumUY, ref SumUZ, ref RX, ref RY, ref RZ, ref SumRX, ref SumRY, ref SumRZ);</code>
<b>Description</b>	Reports the modal participating mass ratios for each mode of the selected modal load case.
<b>Code</b>	<code>ret = myModel.AreaObj.GetAllAreas(ref NumberOfAreaNames, ref AreaName, ref DesignOrientation, ref NumberBoundaryPts, ref PointDelimiter, ref PointNames, ref PointX, ref PointY, ref PointZ);</code>
<b>Description</b>	Retrieves basic data for all area objects in the model.

Application of BIM using Revit and Other Conventional Structural Design Software: A  
Case Study on a High-Rise Building

<b>Code</b>	<code>ret = myModel.AreaObj.GetPoints(AreaName, ref NumberPoints, ref Point);</code>
<b>Description</b>	Retrieves the names of the point objects that define an area object.
<b>Code</b>	<code>ret = myModel.AreaObj.GetProperty(AreaName, ref PropName);</code>
<b>Description</b>	Retrieves the area property assigned to the specified area object.
<b>Code</b>	<code>ret = myModel.PropArea.GetSlab(PropName, ref SlabType, ref ShellType, ref MatProp, ref Thickness, ref color, ref notes, ref GUID);</code>
<b>Description</b>	Retrieves property data for the specified slab section
<b>Code</b>	<code>ret = myModel.AreaObj.GetLabelFromName(AreaName, ref Label, ref Story);</code>
<b>Description</b>	Retrieves the label and story of an area object using its unique name.
<b>Code</b>	<code>ret = myModel.AreaObj.GetLoadUniform(AreaName, ref NumberOfLoads, ref NameOfArea, ref LoadPat, ref Csys, ref Dir, ref Value);</code>
<b>Description</b>	Retrieves the uniform load assigned to a specified area objects.
<b>Code</b>	<code>ret = myModel.Results.AreaStressShell(SlabName, ItemTypeElm, ref NumberResults, ref Obj, ref Elm, ref PointElm, ref LoadCase, ref StepType, ref StepNum, ref S11Top, ref S22Top, ref S12Top, ref SMaxTop, ref SMinTop, ref SAngleTop, ref SVMTop, ref S11Bot, ref S22Bot, ref S12Bot, ref SMaxBot, ref SMinBot, ref SAngleBot, ref SVMBot, ref S13Avg, ref S23Avg, ref SMaxAvg, ref SAngleAvg);</code>
<b>Description</b>	Reports the area stresses for the specified area elements( that are assigned shell section properties) for the specified load case.
<b>Code</b>	<code>ret = myModel.Results.AreaForceShell(SlabName, ItemTypeElm, ref NumberResults, ref Obj, ref Elm, ref PointElm, ref LoadCase, ref StepType, ref StepNum, ref F11, ref F22, ref F12, ref FMax, ref FMin, ref FAngle, ref FVM, ref M11, ref M22, ref M12, ref MMax, ref MMin, ref MAngle, ref V13, ref V23, ref VMax, ref VAngle);</code>
<b>Description</b>	Reports the area force for the specified area elements( that are assigned shell section properties) for the specified load case.
<b>Code</b>	<code>ret = myModel.Results.AreaStrainShell(SlabName, ItemTypeElm, ref NumberResults, ref Obj, ref Elm, ref PointElm, ref LoadCase, ref StepType, ref StepNum, ref e11top, ref e22top, ref g12top, ref emaxtop, ref emintop, ref eangletop, ref evmtop, ref e11bot, ref e22bot, ref g12bot, ref emaxbot, ref eminbot, ref eanglebot, ref evmbot, ref g13avg, ref g23avg, ref gmaxavg, ref gangleavg);</code>
<b>Description</b>	Reports the area strain for the specified area elements( that are assigned shell section properties) for the specified load case.
<b>Code</b>	<code>ret = myModel.DesignConcrete.GetSummaryResultsBeam(Name, ref NumberItems, ref Frames, ref ResultLocation, ref TopCombo, ref TopArea, ref BotCombo, ref BotArea, ref VMajorCombo, ref VMajorArea, ref TLCombo, ref TLArea, ref TTCombo, ref TTArea, ref ErrorSummary, ref WarningSummary);</code>
<b>Description</b>	Retrieve the concrete design results for all beams in the model
<b>Code</b>	<code>ret = myModel.DesignConcrete.GetSummaryResultsColumn(ColumnName, ref NumberItems, ref FrameName, ref MyOption, ref ResultLocation, ref PMMCombo, ref PMMArea, ref PMRatio, ref VMajorCombo, ref AVMajor, ref VMinorCombo, ref AVMinor, ref ErrorSummary, ref WarningSummary, ItemType);</code>

<b>Description</b>	Retrieves column concrete design results
<b>Code</b>	<code>ret = myModel.SpandrelLabel.GetNameList(ref NumberOfSpandrel, ref NameOfSpandrel, ref MultiStory);</code>
<b>Description</b>	Retrieves the names of all defined Spandrel labels.
<b>Code</b>	<code>ret = myModel.DesignShearWall.GetSpandrelSummaryResults(ref SpandrelStoryList, ref SpandrelNameList, ref SpandrelStationList, ref SpandrelTopRebarList, ref SpandrelTopRebarRatioList, ref SpandrelTopRebarComboList, ref SpandrelMuTopList, ref SpandrelBotRebarList, ref SpandrelBotRebarRatioList, ref SpandrelBotRebarComboList, ref SpandrelMuBotList, ref SpandrelAVertList, ref SpandrelAHorzList, ref SpandrelShearComboList, ref SpandrelVuList, ref SpandrelADiagList, ref SpandrelShearDiagComboList, ref SpandrelVuDiagList, ref SpandrelWarnMsgList, ref SpandrelErrMsgList);</code>
<b>Description</b>	Retrieves the summary of wall spandrel design.
<b>Code</b>	<code>ret = myModel.PierLabel.GetNameList(ref NumberPierNames, ref PierName);</code>
<b>Description</b>	Retrieves the names of all defined Pier labels.
<b>Code</b>	<code>ret = myModel.DesignShearWall.GetPierSummaryResults(ref StoryName, ref PierLabel, ref Station, ref DesignType, ref PierSecType, ref EdgeBar, ref EndBar, ref BarSpacing, ref ReinfPercent, ref CurrPercent, ref DCRatio, ref PierLeg, ref LegX1, ref LegY1, ref LegX2, ref LegY2, ref EdgeLeft, ref EdgeRight, ref AsLeft, ref AsRight, ref ShearAv, ref StressCompLeft, ref StressCompRight, ref StressLimitLeft, ref StressLimitRight, ref CDepthLeft, ref CLimitLeft, ref CDepthRight, ref CLimitRight, ref InelasticRotDemand, ref InelasticRotCapacity, ref NormCompStress, ref NormCompStressLimit, ref CDepth, ref BZoneL, ref BZoneR, ref BZoneLength, ref WarnMsg, ref ErrMsg);</code>
<b>Description</b>	Retrieves the summary of wall pier design.
<b>Code</b>	<code>ret = myModel.PierLabel.GetSectionProperties(PierName, ref NumberStories, ref StoryName, ref AxisAngle, ref NumAreaObjs, ref NumLineObjs, ref WidthBot, ref ThicknessBot, ref WidthTop, ref ThicknessTop, ref MatProp, ref CGBotX, ref CGBotY, ref CGBotZ, ref CGTopX, ref CGTopY, ref CGTopZ);</code>
<b>Description</b>	Retrieves the section properties for a specified wall pier.

**Table 11: Code from ETABS and SAFE tools source code: Using ETABS/SAFE output files**

<b>Code</b>	<pre> public string ConnectionString(string FileName, string Header) {     OleDbConnectionStringBuilder Builder = new     OleDbConnectionStringBuilder();      If (Path.GetExtension(FileName).ToUpper() == ".XLS")     {         Builder.Provider = "Microsoft.Jet.OLEDB.4.0";         Builder.Add("Extended Properties", string.Format("Excel         8.0;IMEX=1;HDR={0};", Header));     }     else     {         Builder.Provider = "Microsoft.ACE.OLEDB.12.0";         Builder.Add("Extended Properties", string.Format("Excel         12.0;IMEX=1;HDR={0};", Header));     }     Builder.DataSource = FileName;      return Builder.ConnectionString; }  var query = "SELECT * FROM [" + sheetName + "]"; using (OleDbConnection cn = new OleDbConnection {     ConnectionString = ConnectionString(FileName, "No") }) {     using (OleDbCommand cmd = new OleDbCommand {CommandText =     query, Connection = cn })     {         {             cn.Open();             OleDbDataReader dr = cmd.ExecuteReader();             dt.Load(dr);         }     } } </pre>
<b>Descriptions</b>	Read an ETABS/SAFE output file in Microsoft office excel file format.
<b>Code</b>	<pre> Connection = new OleDbConnection(@"Provider=Microsoft.ACE.OLEDB.12.0;Data Source = " + FileName); Connection.Open(); Command.Connection = Connection; Query = "select * from [TITLE]"; Command.CommandText = Query; da = new OleDbDataAdapter(Command); dt = new DataTable(); da.Fill(dt); </pre>
<b>Descriptions</b>	Read an ETABS/SAFE output file in Microsoft office access file format
<b>Code</b>	<pre> for (int i = 0; i &lt; dt.Rows.Count; i++) {     RequiredData.Add(dt.Rows[i][3]); } </pre>
<b>Descriptions</b>	Extract required data from ETABS/SAFE output file.

**Table 12: Code from Revit plugin source code**

<b>Code</b>	<code>public class DataAssigning:IExternalCommand</code>
<b>Descriptions</b>	Denote the Class “DataAssigning” as the implementation of a Revit add-in external command
<b>Code</b>	<code>public Result Execute(ExternalCommandData commandData, ref string message, ElementSet elements)</code>
<b>Descriptions</b>	Implement an external command within Revit.
<b>Code</b>	<code>UIApplication uiapp = commandData.Application;</code>
<b>Descriptions</b>	Provides access to the Revit application.
<b>Code</b>	<code>Document doc = uiapp.ActiveUIDocument.Document;</code>
<b>Descriptions</b>	Provides access to the active document in Revit.
<b>Code</b>	<code>ElementId ElemID = new ElementId(IDNo);</code>
<b>Descriptions</b>	Create an ElementId handle with the provided integer id number.
<b>Code</b>	<code>Element Elem = commandData.Application.ActiveUIDocument.Document.GetElement(ElemID);</code>
<b>Descriptions</b>	Gets the Element referenced by the given ElementId.
<b>Code</b>	<code>Transaction t = new Transaction(doc, "parameter") t.Start("parameter ");</code>
<b>Descriptions</b>	Starts a transaction. Any change to Revit document can only be done while a transaction is open. The changes become part of the Revit document after being committed and they can be rolled back.
<b>Code</b>	<code>t.Commit();</code>
<b>Descriptions</b>	Commits changes made during an active transaction to the Revit document.
<b>Code</b>	<code>parameter = Elem.LookupParameter("Parameter Name");</code>
<b>Descriptions</b>	Attempts to find a parameter with the given name on an element.
<b>Code</b>	<code>UnitUtils.ConvertToInternalUnits(Value, DisplayUnitType)</code>
<b>Descriptions</b>	Converts parameter value from a given display unit to Revit's internal units.
<b>Code</b>	<code>parameter.Set(Parameter);</code>
<b>Descriptions</b>	Sets the parameter to a new provided value.
<b>Code</b>	<code>return Result.Succeeded;</code>
<b>Descriptions</b>	Informs Revit that the external application completed its task successfully.
<b>Code</b>	<code>Return Result.Failed;</code>
<b>Descriptions</b>	Informs Revit that the external application was unable to complete its task.