STRUCTURAL CODE COMPLIANCE USING BUILDING INFORMATION MODELING

FINAL YEAR PROJECT UG 2017

By

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This is to certify that the

Report entitled

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Has been accepted towards the requirements

For the undergraduate degree

Bachelors of Engineering in Civil Engineering

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This thesis is dedicated to our parents.

For their love, support and encouragement throughout our lives

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ABSTRACT

In structural engineering, the design is vetted to confirm that the parameters used are in accordance with the applicable codes. This code compliance checking process is done manually which leads to delays and errors in evaluation. This study aims at the concept of automation in the structural code compliance checking through Building Information Modeling (BIM). The idea is to eliminate the human error in the process. The study develops a BIM-based framework to automate the code checking process for a structural design for ACI 318-14 and ASCE 7-10 codes. The framework is used to create a plugin for BIM platform named Autodesk Revit by using a visual programming software named Dynamo. The developed plugin demonstrates the automation in a BIM-based platform that can reduce the time required for structural design vetting.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institution
AEC	Architecture, Engineering & Construction
BIM	Building Information Modeling
VPL	Visual Programming Language
CORENET	Construction and Real Estate Network
EDM	Express Data Management
ASCE	American Society of Civil Engineers
CAD	Computer-Aided Design
NBIMS-US	National BIM Standard-United States
RISA	Rapid Interactive Structural Analysis
ETABS	Extended Three-Dimensional Analysis of Building System
SAP	Structural Analysis Program
CSI	Computers and Structures, Inc.
API	Application Programming Interface
GUI	Graphical User Interface
PDF	Portable Document Format

Chapter 1

INTRODUCTION

1.1 Background

There are numerous standards and codes in the AEC industry that ensure the structural stability, reliability, usability of the building under design. The adherence of the building design to these guidelines is a critical process (Preidel & Borrmann, 2016).

Code compliance, is compliance with a written, approved or required set of rules that have been set into a code format. The compliance checking process must occur constantly throughout all the phases of a project. It should be carried out for the architectural aspect of a project, the structural aspect or any other aspect.

Once a building is structurally designed, that design is vetted against the applicable structural codes to ensure that the design meets all the relevant standards for safety. stability, durability and serviceability accordingly. Failure to follow construction and safety codes is the most common cause of building collapse (Lodhi, 2020), so the codes must be followed.

Despite the fact that every building project is now digitally modeled, compliance checking is still a manual process, which increases delays and also the risk of evaluation errors (Eastman, et al., 2009). The McGraw-Hill Construction SmartMarket Report (2007) says that in the 39 percent of the cases investigated, compliance checking took 25 hours or more, and more than 100 hours in 11 percent of the cases. The report stated that it took between 49 and 60 hours for the compliance checking process. As a result, it is obvious that automated code compliance checking should be implemented.

An automated code compliance checking system, as defined by Nawari (2018), is a computational procedure for dealing with the manual code compliance problem. The goal is to improve the manual design review process by rationalizing the information of a predictable outcome. It entails the automatic deduction and verification of certain details that can take a very long time to perform manually.

Designers would benefit from automated code compliance checking, as would consultants, building certifiers, building code authorities, specification writers and builders (Tan, Hammad, & Fazio, 2010).

1.2 Problem Statement

We can see the automated code compliance being realized in CORENET e-Plan Check, Australia Design Check, Solibri Model Checker, EDM modelChecker, etc., but these are all of architectural nature. The automated code compliance for structural engineering is yet to be properly introduced. When BIM was first introduced, it mainly focused on the architectural field, however, as different industries evolved and adopted BIM, the various BIM software are constantly evolving to meet the desires of structural engineers, providing improved tools that enhance its use in the structural engineering field (Hunt, 2013). Building information models allow structural engineers to more accurately, efficiently and competitively design, visualize, simulate, analyze, document and build projects (Autodesk, 2012).

The structural design vetting process is carried out by the consultant, relative authorities for the approval of the design. The process today is done completely manually, at least in Pakistan. The process includes rules and calculations that are applied on the structural model for which the results could take up to days. Also, it costs a lot for the design to be vetted by a professional structural engineer. For these reasons, the structural design vetting process is like a mere formality in Pakistan and it is not given serious attention, which results in a non-compliant design, leading to life-threatening situations (Aslam, 2020). In a study conducted by ASCE of around 600 failed structures, approximately 36 percent of the structures failed due to improper designs during the preconstruction phase (Panwar, 2021).

Keeping these points in mind, it is high time that a system is introduced that paves way for a planned structural code compliance process.

1.3 Objectives

The study has the following objectives:

- To identify and assess the existing problems faced in the structural design vetting process.
- To develop a framework for Automated Code Compliance checking through BIM-based visual programming.
- To develop a digital platform for the realization of the framework.

1.4 Areas of Application

The work in this project can be used by anyone working in a BIM environment tasked with performing the structural code compliance process. Other than that, it can be used by any of the project stakeholders in order to know the structural details of the model. This project has used ACI 318-14, along with ASCE 7-10. However, the work can be replicated using any other required code.

1.5 Thesis Organization

This thesis has been organized into five chapters, as shown in Figure 1.1. An overview of those chapters is given below.

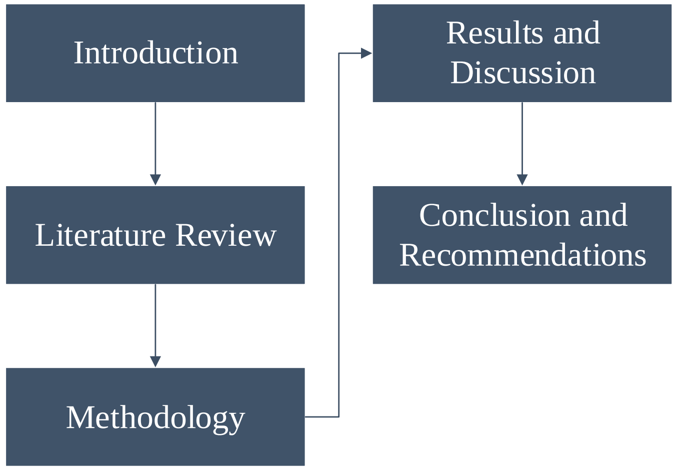


Figure 1.1 Thesis Organization

Chapter 1 is an introduction to the project, which includes the background of the project, problem statement, objectives and the areas where the project is applicable.

Chapter 2 is the literature review that was done for the project. This mainly includes the concepts of BIM and the automation in AEC industry.

Chapter 3 explains the methodology that was adopted in the project. This includes the framework and the code that was generated.

Chapter 4 discusses the results of the project, mainly the developed Autodesk Revit plugin and its buttons. It also compares the manual and the automated code compliance process.

Chapter 5 is a conclusion to the project, along with recommendations as to how to use the work in this project for the better.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review that is aimed at establishing a theoretical understanding of the concept of Building Information Modeling (BIM) and automated code compliance. The areas of interest for the literature review are BIM as a concept, BIM in structural engineering, automation of code compliance process and its importance in the AEC industry. The sources have mainly been research articles and books.

2.2 Building Information Modeling (BIM)

Building Information Modelling (BIM) is defined as a modeling technology and related set of processes for creating, communicating, and analyzing building models (Eastman, et al., 2008). BIM can decrease information losses because models and information should ideally follow the entire building process and be created only once (Sandberg, et al., 2016).

According to the US National BIM Standard (NBIMS-US, 2015), Building Information Modeling (BIM) is a digital representation of a facility's physical and functional characteristics. BIM is a shared knowledge resource for information about a facility that serves as a dependable basis for decisions. BIM provides an information base that is used throughout its entire lifecycle, beginning with the conceptual design phase and progressing through the detailed planning phase to the realization and operation phase (Eastman, et al., 2008).

Building information modeling (BIM) is a prototyping simulation technology and workflow which is being known as a revolutionary process that is currently reforming the Architectural, Engineering, and Construction (AEC) industry (Nawari & Kuenstle, 2015).

In order for the different engineering fields to cooperate effectively, the data of the infrastructure needs to be appropriately organized (Shim, Yun, & Song, 2011). BIM is well-known for its design and documentation abilities, which enable the storage of valuable computable information that remains coordinated and consistent across all its users (Autodesk, 2012). By allowing several team members to work on the same model, BIM facilitates collaboration for architects, structural engineers, mechanical, electrical and plumbing professionals (Bynum, Issa, & Olbina, 2013). BIM is not a goal in and of itself, but rather a tool for achieving higher productivity (Eastman, et al., 2009).

Since BIM is more technical, non-professional clients find it difficult to understand and, in particular, the elderly are reluctant to accept this technology although the benefits are apparent (Vries, Allameh, & Jozam, 2012).

The technological foundation for automated code compliance checking is based on the concept of Building Information Modeling (BIM), which is currently transforming the AEC industry’s working processes. While the benefits of BIM technology for many AEC processes have been researched and documented, its enormous potential for automating the code compliance checking process has yet to be fully realized. (Preidel & Borrmann, 2016).

2.3 BIM and Structural Engineering

Structural engineering includes an extensive variety of skills and competencies that are applicable to all types of projects (Vilutiene, et al., 2019), ranging from minor slope strengthening projects to the design of large-scale structures (Chin, et al., 2008). To make a building and its systems sustainable, safe, and long-lasting, the structural engineer is responsible for developing efficient solutions in the use of structural elements and materials (Sun, Staszewski, & Swamy, 2010). Structural designs must usually be integrated with the outputs of other disciplines, such as architects and engineers of various building services (Pezeshki & Ivari, 2018). The difficulty of the tasks, the required combination of many various skills, and the plenty of different communication channels demand a dependable data exchange platform (Eastman, et al., 2008). To put it another way, maintaining the quality of the final product necessitates the use of tools that allow structural engineers to monitor system parameters under development and verify the reliability of the provided information (Vilutiene, et al.,2019). BIM is one available solution that offers all of these capabilities.

BIM models are geometrically encoded in 3D (Bilal, et al., 2016), in a variety of proprietary formats, with the possibility to add time (4D) and cost data (5D) attached to them. That is, the main idea behind BIM is to provide object-oriented digital representations of buildings in the form of data-rich models, as well as the ability to simulate and analyze these models for design, construction, and operation purposes (Eastman, et al., 2008). Structural engineers can benefit from BIM in a variety of ways, including the ability to keep the model up to date with any changes in the design or general specifications, ensuring all the data is as exact as possible (Azhar, 2011). BIM also allows all stakeholders to experiment with a variety of easily available alternatives and design ideas (Vilutiene, et al., 2019). BIM is not only a quick and easy way to present owners and stakeholders with the various designs and situations related to specific projects, but it also allows members of the design team to better coordinate the fabrication of various building systems, which is one of the reasons for its rapid adoption (Nawari, 2012). There is no doubt that BIM is altering the structural engineering field for the better.

According to Tom Bartley (2017), there are several other benefits that are gained from the adoption of BIM tools and techniques in one’s work:

- integration of analysis and drawing production would enhance efficiency;
- 3D modeling improves the quality by improving coordination and communication;

- a shared data environment helps teams collaborate more effectively within and across departments;
- employing visualization during design reviews to engage non-technical stakeholders;
- increased confidence in the design and the use of the model for prefabrication;
- simulation is used to plan and optimize the project schedule;
- the 3D model can be used to improve site inductions, making safety and risk management more tangible;
- keeping track of inspections to monitor asset performance.

Despite all of the benefits that BIM brings to structural engineering, structural engineers are still hesitant to use it. According to the McGraw-Hill Construction SmartMarket Report (2007), 48 percent of architects consider BIM to be one of the tools they frequently use, while only 35 percent of engineers use BIM. Following in the footsteps of architects, engineers may transition from experimenting with BIM to using it on a significant portion of projects.

2.4 Automated Code Compliance Checking

The process of automatically checking models against guidelines, standards, and other criteria is known as ‘automated code checking’ or ‘code compliance checking’, and it leads to faster, dematerialized and more transparent review processes (Martins, Rangel, & Abrantes, 2016). A construction project is controlled and monitored by the codes, which makes the codes a vital aspect in the AEC industry. The adoption of an automated code checking process improves project effectiveness and enables quick decision-making on a specific issue (Park & Kim, 2015).

McGraw-Hill Construction SmartMarket Report (2007) states that the automated code compliance checking process holds a lot of promise for architects. While three out of every five members of the construction team are intrigued by the concept, architects are by far the most fascinated with 85% expressing interest. The fact that architects share data more frequently than other members of the construction team is fueling this interest. On a typical project, nearly half of architects (48%) spend at least 26 hours on code checking. They then stated that the engineers on the other hand, still appear to be continuing to make efforts to improve the flow of data used for code compliance checking. On a typical project, engineers estimate spending around 51 hours on code checking.

2.5 Autodesk Revit

Revit is a building information modeling software produced by Autodesk. It works similarly to AutoCAD or SketchUp in that it generates a simulated three-dimensional model of a structure (Christenson, 2006). Autodesk Revit is one of the most powerful civil engineering software on the market. It offers a large number of functions and pre-sets, due to which the users can create a sketch of the building from scratch comparatively easier than AutoCAD. Unlike AutoCAD, Revit is equipped with ‘family’ features that save an architect a significant amount of time. This feature is what makes Revit one of the best software to use for a civil engineer (Fakhrutdinov, 2018). Also, Revit is the only complete parametric Building Information Modeling (BIM) tool available today (Mousiadis & Mengana, 2016).

Add-on menus in Autodesk Revit extend the software’s capabilities and functionalities. Extensions differ from supplements in that they are entirely developed and provided by Autodesk, whereas supplements are produced and provided by other companies that collaborate with Autodesk in order to facilitate the modeling of their products (Maia, Mêda, & João, 2015).

The Autodesk Revit Suite has a bidirectional link that allows for easy data transfer with the industry’s most used structural analysis software, such as RISAFloor and RISA 3D by RISA, ETABS and SAP2000 by CSI, and RAM Structural System by Bentley (Hunt, 2013).

2.6 Visual Programming Language (VPL)

A visual language, in general, is defined as a formal language with visual syntax and semantics (Erwig, 1997). A VPL is extremely user-friendly, and it reduces the barriers to entry into the field of programming for ordinary end-users. VPL programs are much easier to create and understand than textual counterparts due to their visual representation and means for intuitive interaction (Preidel, Daum, & Borrmann, 2017).

Some of the prominent VPL products include the plugin Dynamo for Autodesk Revit (or as a standalone application), Grasshopper for Rhinoceros3D and Marionette for Vectorworks. While textual programming languages can be difficult for AEC professionals to work with, visual programming languages are gaining increasing acceptance and widespread use among domain experts because information systems described in a visual language can be understood much more quickly and easily by humans (Preidel & Borrmann, 2016). Many studies show that non-programmers or novice programmers find visual programming languages much easier to understand than the conventional (textual) programing language (Asl, et al., 2014).

Many popular BIM modeling applications, in addition to the more traditional languages such as C# or Python, allow the development of plugins using Visual Programming Languages (VPL). This allows the development of plugins for BIM modeling applications without the need to use the more complex APIs. AEC practitioners with little (or no) coding skills may, therefore, develop code-checking procedures according to their requirements (Martins, Rangel, & Abrantes, 2016).

Ritter, et al. (2015) reviews the state of the art of visual programming languages and summarizes the application domains of visual programming languages in civil engineering, including inquiry languages, geometric modeling, knowledge-based design, design decision support, systems modeling and code checking.

Preidel, et al. (2017) are working on a visual code checking language, that is intended to perform compliance checks automatically (or semi-automatically) and significantly improve the overall process efficiency and quality.

2.6.1 Dynamo

Dynamo is a free software application that can be run standalone or as a Revit plugin. Dynamo is basically a visual programming tool that is designed to be user-friendly for both the non-programmers and the programmers. It allows users to visually script behaviour, define custom pieces of logic, and script using the several textual programming languages (Mousiadis & Mengana, 2016). With the visual programming environment Dynamo, engineers can extend and automate recurring tasks in Revit (Esser & Aicher, 2019).

By connecting ‘nodes’ with ‘wires’, to indicate the logical flow of the resulting visual program, Dynamo allows us to develop visual programs in a workspace.

The true power of Revit as a building information modeling software is not in geometry creation, but in how you can track and manipulate the model information. Dynamo allows users to create systematic relationships to manipulate model elements and parameters in ways that would be impossible with traditional Revit tools. Also, BIM is frequently thought of as a ’production’ tool rather than a design tool. However, Dynamo has the potential to prove this misconception wrong, by allowing designers to experiment with iterative frameworks within the context of a BIM-based tool (Mousiadis & Mengana, 2016).

The Dynamo Development team at Autodesk says that Dynamo is literally what you make of it. Working with Dynamo may entail using the application, whether in conjunction with other Autodesk software or not, engaging in a visual programming process, or being a part of a large user community.

2.7 Structural Design Vetting Process

The conformity to the given code should be present at all phases of the project. In the design phase, after a structure is designed, that design is vetted against the structural code, with the main objective being to ensure the primary structural support systems' stability and integrity.

The purpose of the structural design vetting process is to increase confidence in a building's or project's predicted performance and safety as documented in the design criteria, the design approach and structural design documentation.

The structural design vetting is meant to cover an actual assessment of the design using independently generated calculations. It is not just a review of previous structural engineer's calculations. It is carried out to determine whether the building or structure complies with the structural code's minimum structural design standards (Lewis & Ranville).

2.8 Structural Codes

Code references and standards are the factors needed to make the design structurally safe and sound. These codes (e.g., ACI code, Eurocodes, Japanese codes or Chinese codes) serve as a guideline in our design, making them play a huge role in the industry. The codes differ from country to country based on local conditions. Although Pakistan has made up its own structural code, namely "Building Code of Pakistan", that code is rarely used because it is basically a compilation of codes, mainly ACI 318 and ASCE 7, which are precisely the codes used in this project.

2.9 Structural Checks

In the structural code compliance process, the vetting engineer reviews the inputs that were given while designing, the options used and performs the structural checks. The engineer needs to know what properties were defined for the concrete material, for the frame members, for slabs and for shear walls that were used for the structural model. The engineer also needs to know what types of loads were assigned to the model, the source of the mass of the building, the slab modeling type, the type of diaphragms etc. All of these things are manually checked in the structural designing software. Also, the engineer extracts different analysis results in order to manually perform the calculations for the structural checks.

The structural checks performed in this project are as follows:

- Concrete Materials
- Frames
- Slabs and Shear Walls
- Load Patterns
- Mass Source
- Diaphragms
- Story Drift
- Torsion Irregularity

2.9.1 Stiffness Modifiers

The ability to attract moment, shear, axial force etc. is referred to as stiffness. The stiffer an element, the more force it attracts and the more reinforcement we design for.

Modeling of concrete structural elements by linear analysis to achieve a reasonable structural response usually requires the stiffness of concrete structural elements to be changed (Wong, et al., 2016).

Cracking affects the stiffness of the structure which in result will affect the deflection and forces. Cracking in a section causes variation in the moment of inertia. There is a reduced moment of inertia in cracked regions and a much larger moment of inertia in non-cracked sections. Also, as the load increases, so does the cracking. Therefore, the moment of inertia varies with load.

ACI 318 gives us the values that are to be input as stiffness modifiers (Figure 1.1). For the beams, the moment of inertia is to be input as 0.35Ig. For columns, as 0.7Ig. For slabs, as 0.25Ig. For uncracked walls, as 0.7Ig and for cracked walls, 0.35Ig.

Member and condition		Moment of Inertia	Cross-sectional area
Columns		$0.70I_g$	$1.0A_g$
Walls	Uncracked	$0.70I_g$	
	Cracked	$0.35I_g$	
Beams		$0.35I_g$	
Flat plates and flat slabs		$0.25I_g$	

Figure 2.1 Stiffness Modifiers Values (ACI 318-14, Table 6.6.3.1.1)

2.9.2 Story Drift Check

The story drift is the lateral displacement of one level relative to the level below. It is important to be considered as it aims to ensure the acceptable performance of a structure. The larger the drift, the less stiff the structure is.

Inelastic displacement, δ_x is the actual displacement, calculated by multiplying the elastic displacement, δ_{xe} by the deflection amplification factor, C_d (chosen from Table 12.2-1 of ASCE 7-10 based on the type of seismic force-resisting system) divided by the importance factor, I_e (determined in accordance with Section 11.5.1 of ASCE 7-10).

$$\delta_x = \frac{C_d \delta_{xe}}{I_e}$$

Because story drift criteria are one of the main considerations in selecting the right lateral structural system, all of the factors that influence the drift should be carefully considered. Figure 2.2 shows how the story drift is determined.

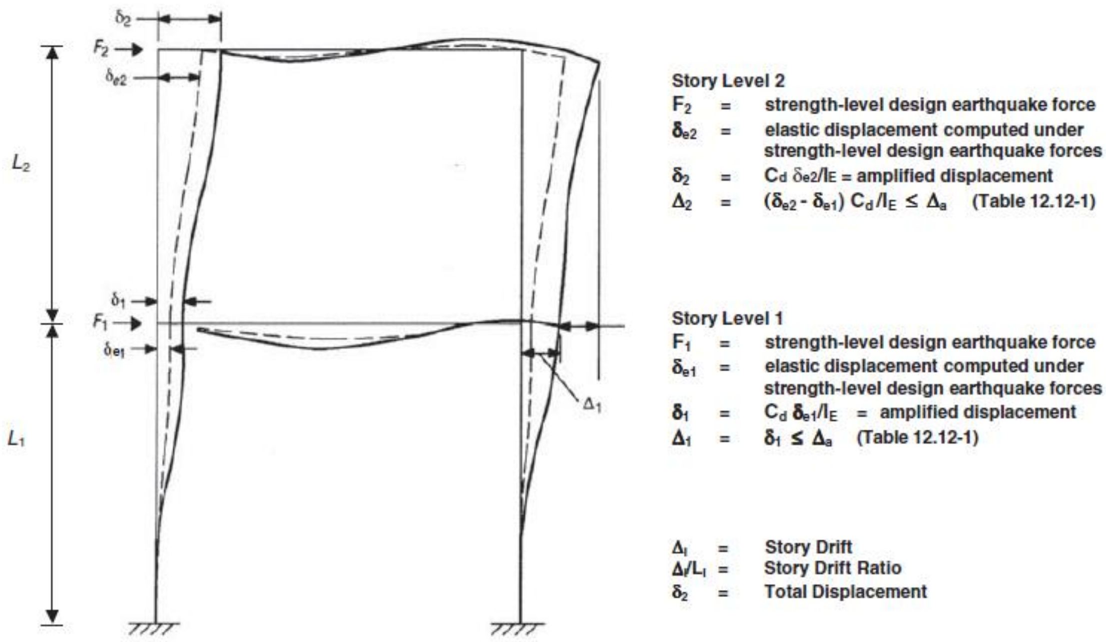


Figure 2.2 Story Drift Determination (ASCE 7-10, Figure 12.8-2)

ASCE 7-10 sets the allowable drift limits, as shown in Figure 2.3. These are the functions of seismic forces resisting system's risk category and type.

Structure	Risk Category		
	I or II	III	IV
Structures, other than masonry shear wall structures, 4 stories or less above the base as defined in Section 11.2, with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts.	$0.025h_{sx}{}^{c}$	$0.020h_{sx}$	$0.015h_{sx}$
Masonry cantilever shear wall structures[d]	$0.010h_{sx}$	$0.010h_{sx}$	$0.010h_{sx}$
Other masonry shear wall structures	$0.007h_{sx}$	$0.007h_{sx}$	$0.007h_{sx}$
All other structures	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$

Figure 2.3 Allowable Story Drift (ASCE 7-10, Table 12.12-1)

2.9.3 Torsion Irregularity Check

Torsional irregularity is a well-known concept. For decades, it has been expressed in various codes. It is a problem that engineers have learned to deal with, especially in seismically active areas (Johnson, 2015). Torsional irregularities influence the structure's drift and must be considered for structures with rigid diaphragms (Al-sheikh, 2019), as is typically the case. If torsion irregularity exists, an amplification factor is to be applied to normalize the stiffness of the building.

Torsional irregularity exists when the maximum story drift at one end of the structure transverse to an axis exceeds 1.2 times the average of the story drifts at both ends of the structure. Extreme torsional irregularity exists where the maximum story drift at one end of the structure transverse to an axis exceeds 1.4 times the average of the story drifts at both ends of the structure.

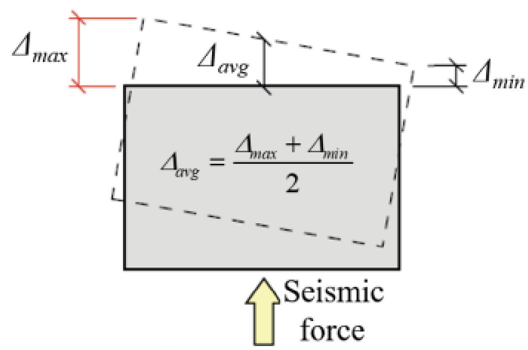


Figure 2.4 Story Drift for Torsion Irregularity (FEMA P-2012)

2.10 ETABS

ETABS which stands for "Extended 3D Analysis of Building Systems" is basically a 3D structural Finite Element analysis program. It is very popular and is focused on the analysis and design of buildings. This also means that ETABS has its own 3D building component modeling environment like Revit. Using the API to extract data and analysis results (like how Dynamo works with Revit) is very advantageous and this can be done with ETABS too (Sgambelluri, 2018). Therefore, ETABS has been chosen for this project as the structural designing software.

Chapter 3

METHODOLOGY

3.1 Introduction

The methodology adopted to achieve the objectives introduced in chapter 1 is discussed and presented in this chapter. The work in this project consists of nine steps. Initially, a detailed literature review was carried out. The aims of the literature review were to develop an understanding of BIM and automated code compliance processes. After that was accomplished, we acquired some CAD drawings in order to draw a structural model. We then selected the structural codes that were to be used in the project, which were ACI 318-14 and ASCE 7-10, as these are the codes that are usually used in Pakistan. The structural model was then created using the acquired CAD drawings in ETABS. After that, a BIM-based framework was developed for the automation process. We then moved on to Dynamo to generate the code which obeyed the rules set in the generated framework. After the code was generated, we applied it to the created structural model. The results were then generated.

The steps are shown in Figure 3.1.

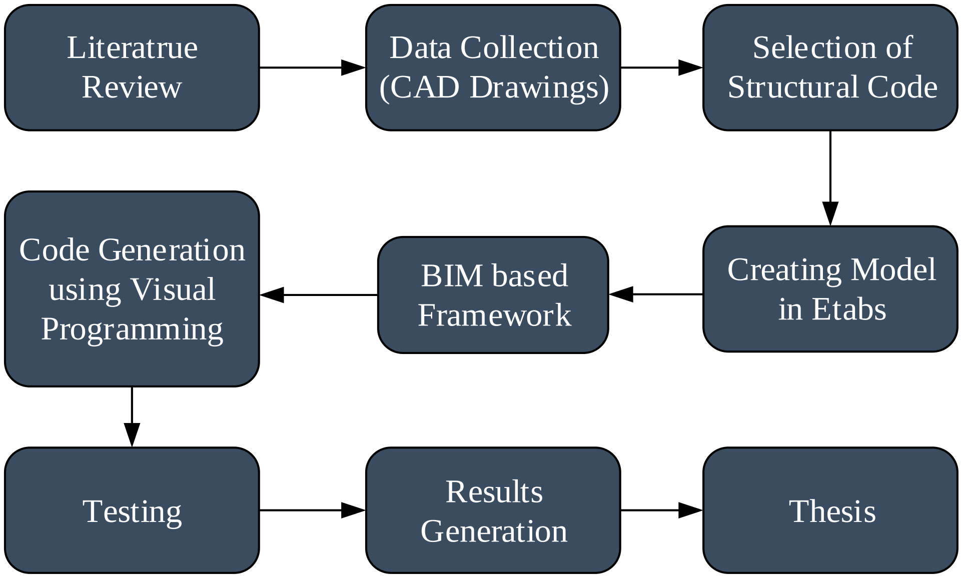


Figure 3.1 Methodology

3.2 Structural Designing Software Selection

The structural engineering firm is primarily responsible for the structural designing software selection. Different structural analysis programs are usually familiar to structural engineers. The initial selection of BIM and structural engineering software is therefore based on the software currently being used by the engineering firm (Hunt, 2013). In Pakistan, almost all the designing firms use ETABS, therefore, in order for this project to be an aid to those designing firms, it was imperative that we use ETABS for this project.

3.3 Structural Model

After the acquisition of the CAD drawings of a six-story plaza in Lahore, Pakistan, its model was created in ETABS. Figure 3.2 shows a rendered view of the model.

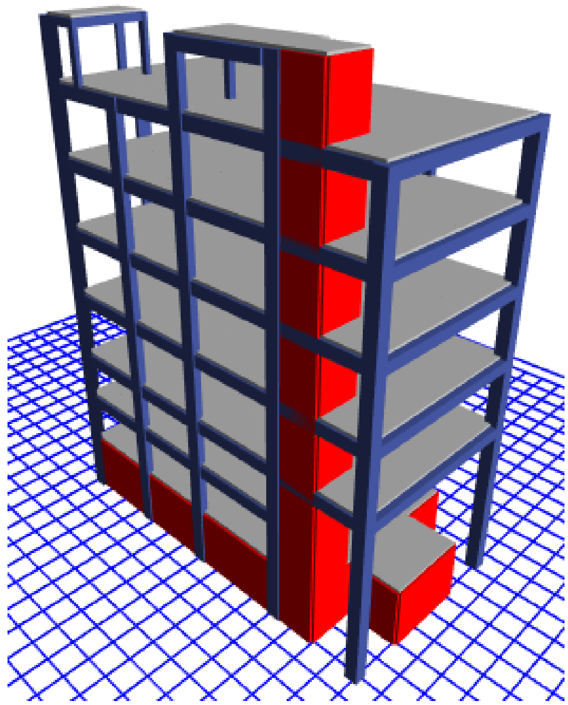


Figure 3.2 Structural Model

3.4 BIM Based Framework

For the automation of the process, a BIM-based framework was generated which was followed while generated the code in Dynamo. The framework has three main steps. The first is set-up, the second is code compliance check and the third is the result. The process initiates by running the structural model and when it is up and running, the code in Dynamo is run on that structural model. The results will be generated, which would then be organized or sorted. Then, those organized results will be evaluated against the structural codes ACI 318-14 and ASCE 7-10. The non-compliant results would be displayed and a report containing all the results will be generated.

The framework is illustrated in Figure 3.3.

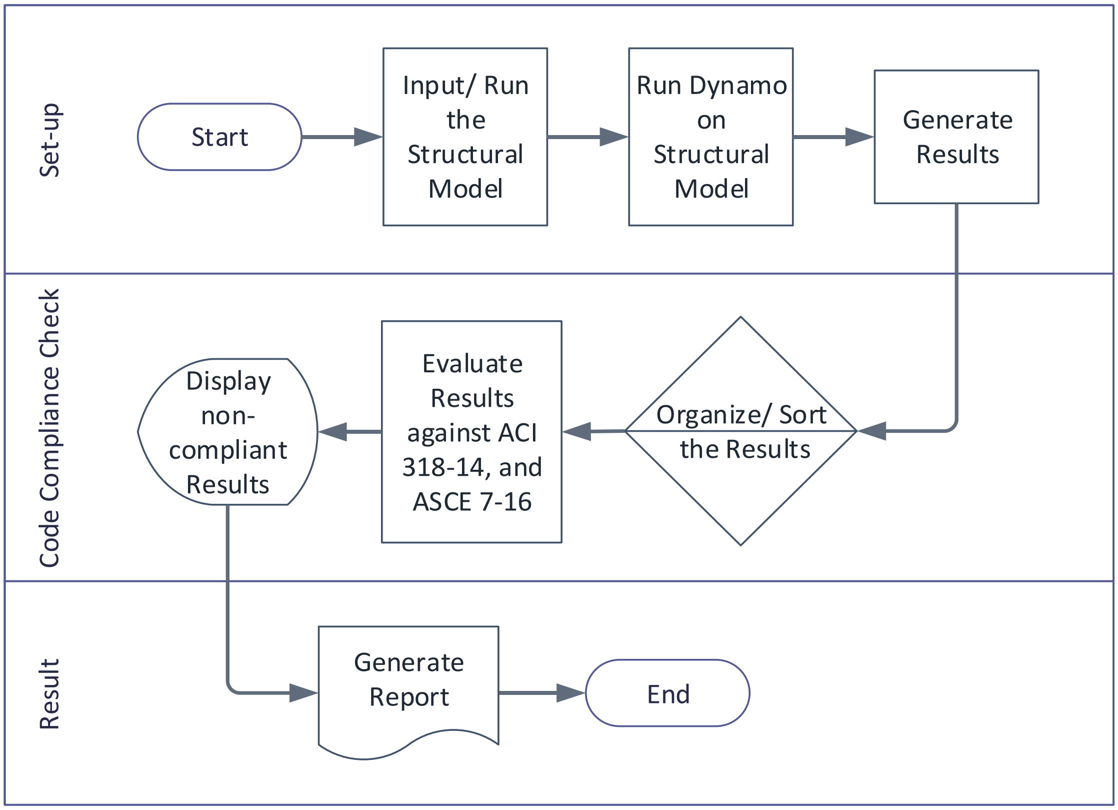


Figure 3.3 Framework

3.5 Code Generation using Dynamo

Dynamo was used to generate the code for the automated code compliance procedure. In order to interact with the structural model in ETABS, a package in Dynamo, called “Simplex”, created by Marcello Sgambelluri, BIM director at John A. Martin & Associates, was used.

The reality is most of the "data" that is extracted from these structural analysis models is done using a "manual" process. For example, to verify geometric relationships between beams and columns or columns and walls the user needs to manually open each element in ETABS or SAP and verify that information manually. This process is tedious and time-consuming that takes up the engineer’s time and the company’s budget. Revit has gone through an evolution where Revit users now are able to interact with the Revit model using Dynamo and the Revit API to automate tasks. It’s time to use that same technology on the structural analysis models (Sgambelluri, 2018). Hence, the package "Simplex" was created for this very purpose.

The use of an Application Programming Interface (API) allows for the development of highly adaptable analysis solutions for a variety of structures. APIs are the key component that enables data to flow between BIM software and structural analysis software (Hunt, 2013). The code in Dynamo was created for each of the structural checks separately, using the ETABS API.

3.6 Concrete Materials, Mass Source, Diaphragms and Load Patterns

For concrete materials (Figure 3.4), mass source (Figure 3.5), diaphragms (Figure 3.6) and load patterns (Figure 3.7), the defined properties, the options selected, the defined loads are first extracted from the structural model to Dynamo, those results are then sorted and organized. The organized results are then displayed in a Graphical User Interface (GUI).

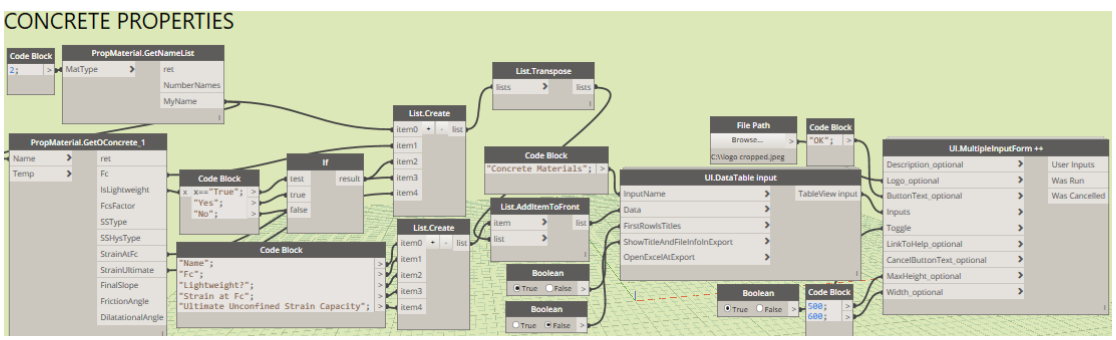


Figure 3.4 Code for Concrete Properties

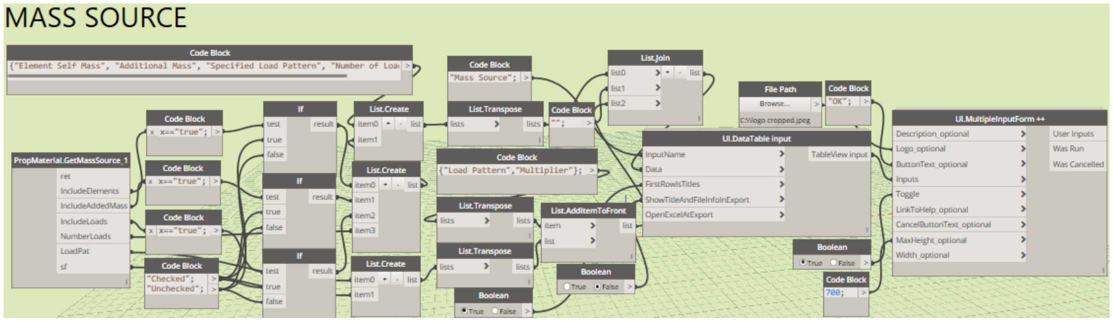


Figure 3.5 Code for Mass Source

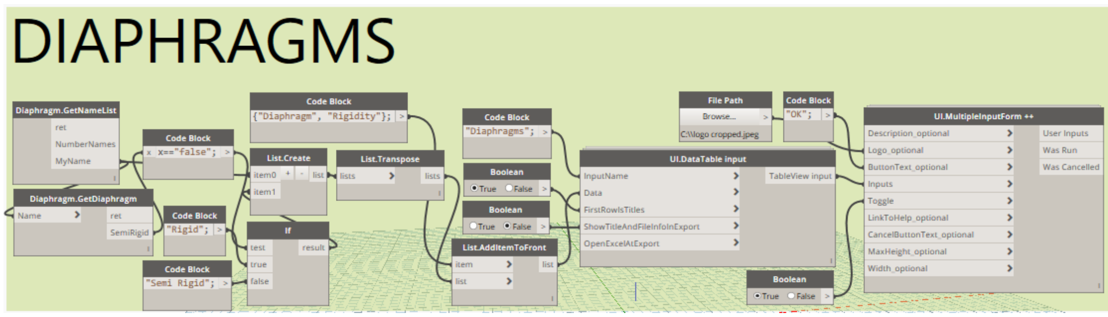


Figure 3.6 Code for Diaphragms

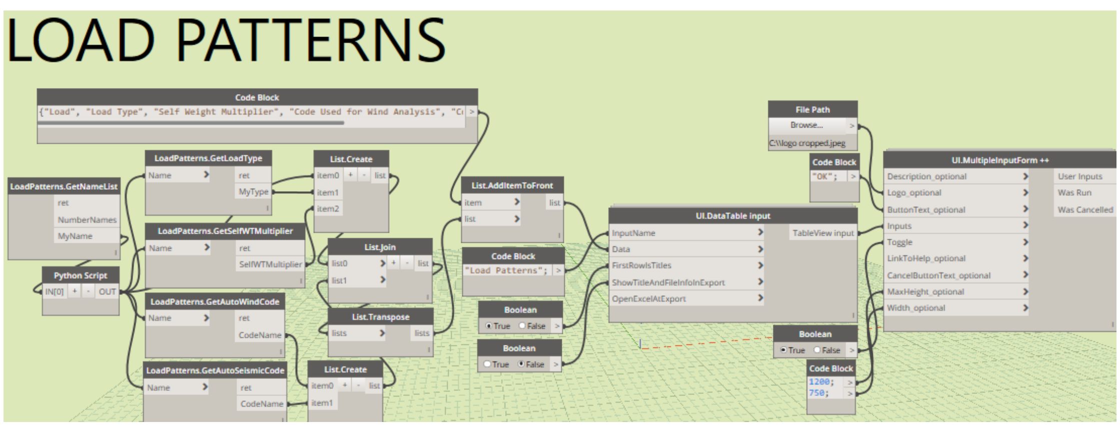


Figure 3.7 Code for Load Patterns

3.7 Frames, Slabs and Shear Walls Properties

To check frames (Figure 3.8), slabs and shear walls (Figure 3.9) properties and modifiers, the properties and assigned modifiers are first extracted from the structural model to Dynamo, those are then sorted and organized. The organized results are then compared with the values given by the structural code. All the non-compliant members will then be displayed in a GUI, also indicating the frame/s, slab/s or shear wall/s that need to be revised.

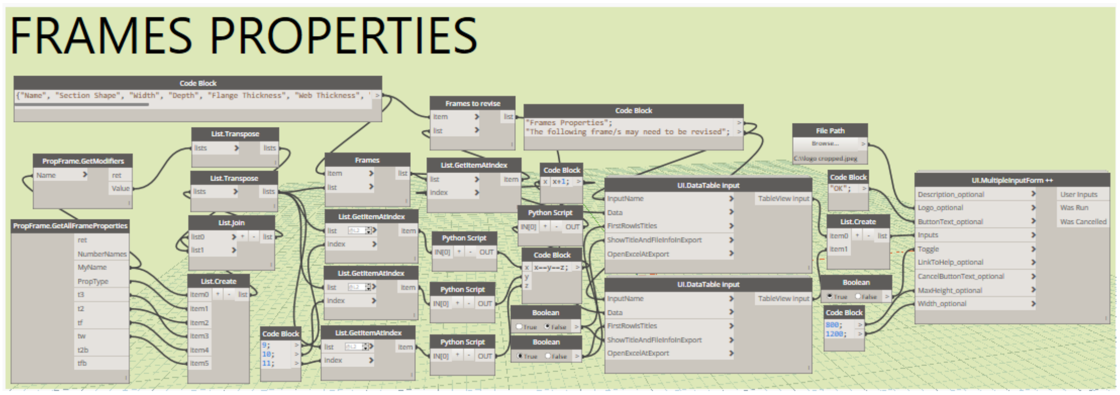


Figure 3.8 Code for Frames Properties

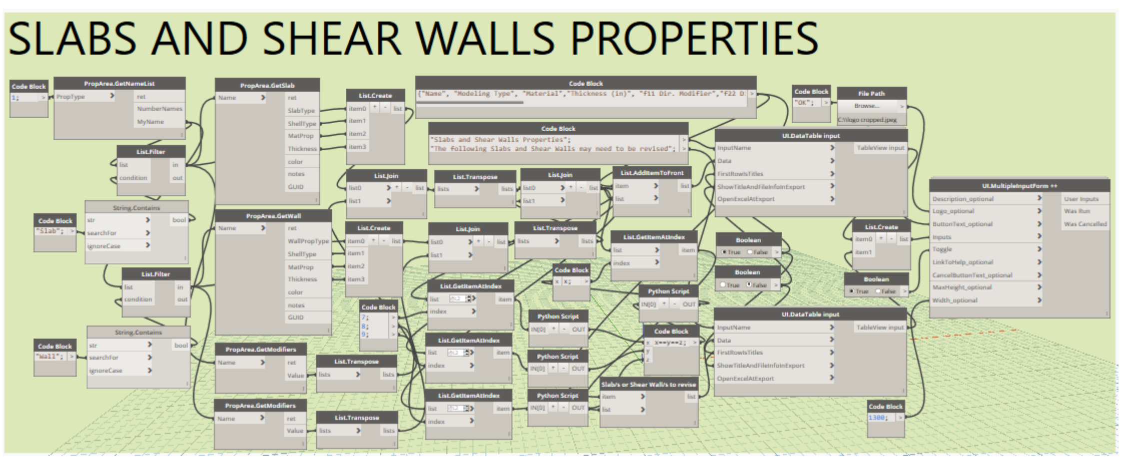


Figure 3.9 Code for Slabs and Shear Walls Properties

3.8 Story Drift and Torsion Irregularity Check

For story drift (Figure 3.10 to Figure 3.13) and torsion irregularity (Figure 3.14 and Figure 3.15) check, the analysis results are first extracted from the structural model, followed by sorting and organizing those results. The organized results then undergo calculations in order to know whether the story drift or torsion irregularity is under the prescribed limit mentioned in the structural code or not. The results are then displayed in a GUI showing whether the structure is safe or not.

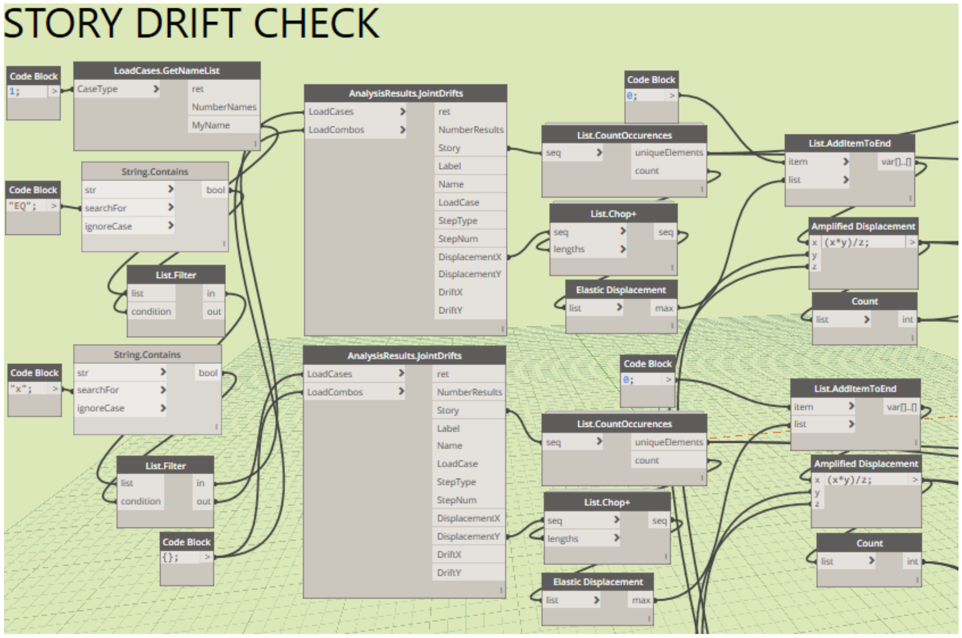


Figure 3.10 Code for Story Drift Check (a)

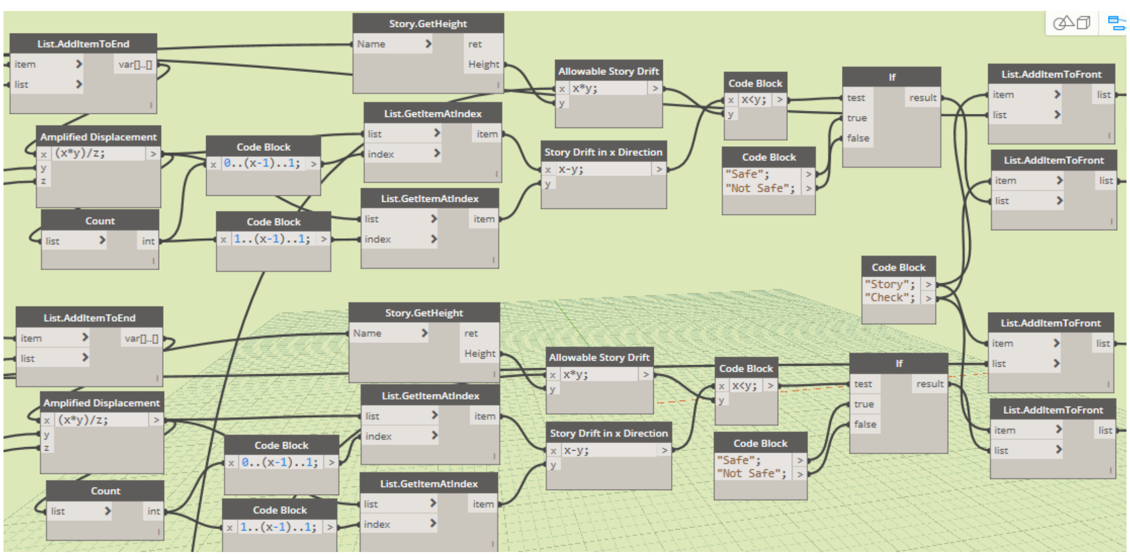


Figure 3.11 Code for Story Drift Check (b)

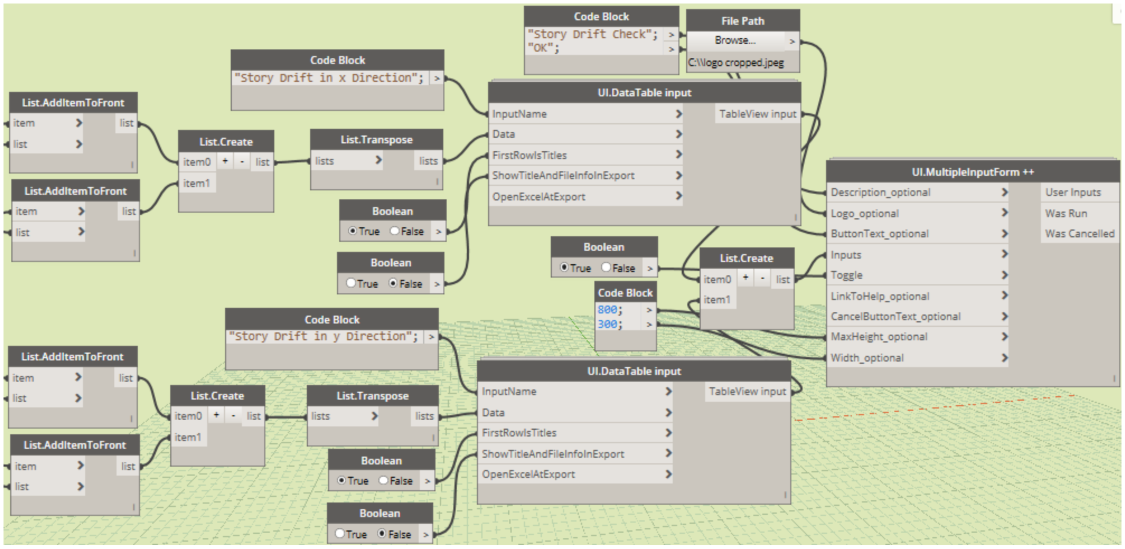


Figure 3.12 Code for Story Drift Check (c)

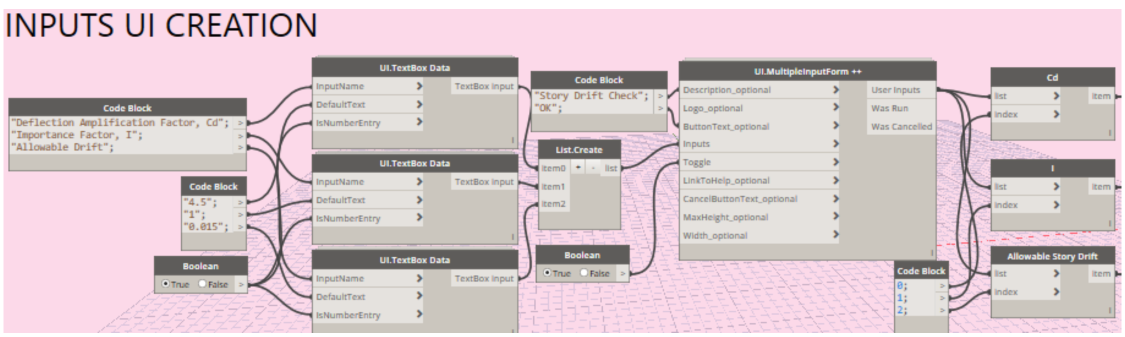


Figure 3.13 Code for Story Drift Check (d)

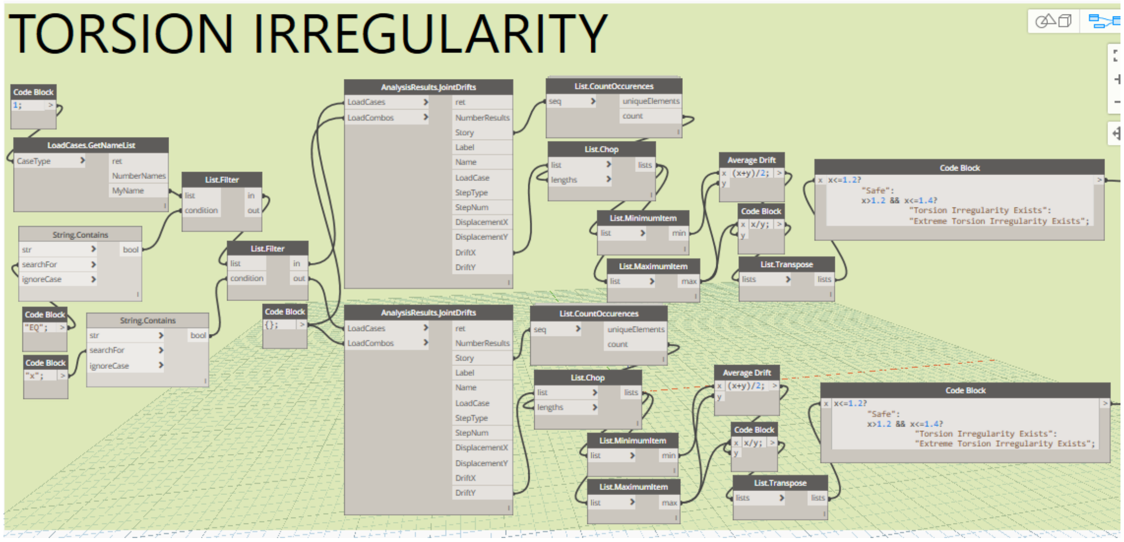


Figure 3.14 Code for Torsion Irregularity Check (a)

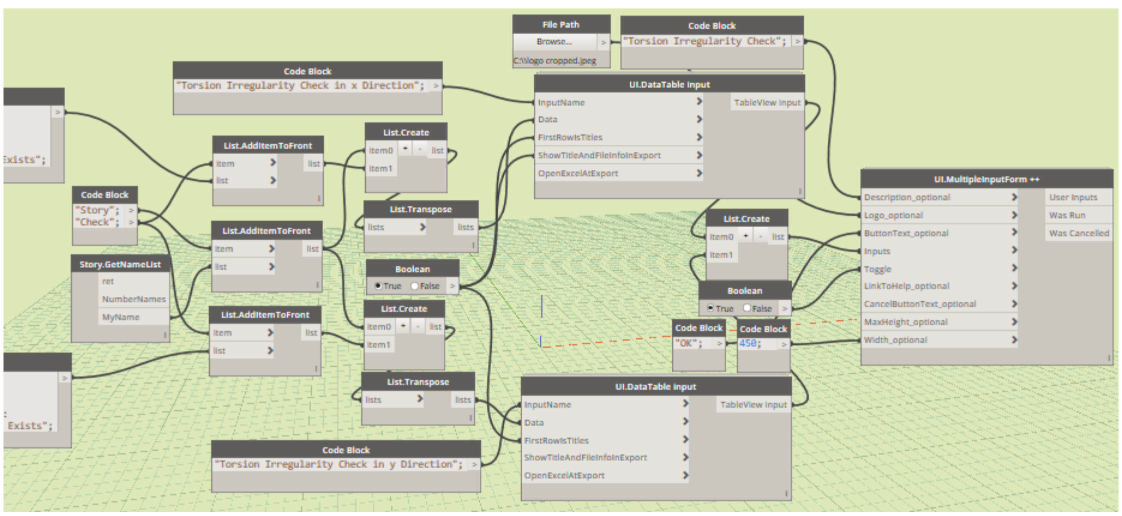


Figure 3.15 Code for Torsion Irregularity Check (b)

RESULTS AND DISCUSSION

4.1 User Interface

In order to ensure that the automated structural code compliance process is easily performed by anyone, with or without extensive structural design knowledge, a plugin for Autodesk Revit was created, namely “Design Check”. Figure 4.1 shows the plugin present in the top ribbon of Autodesk Revit.

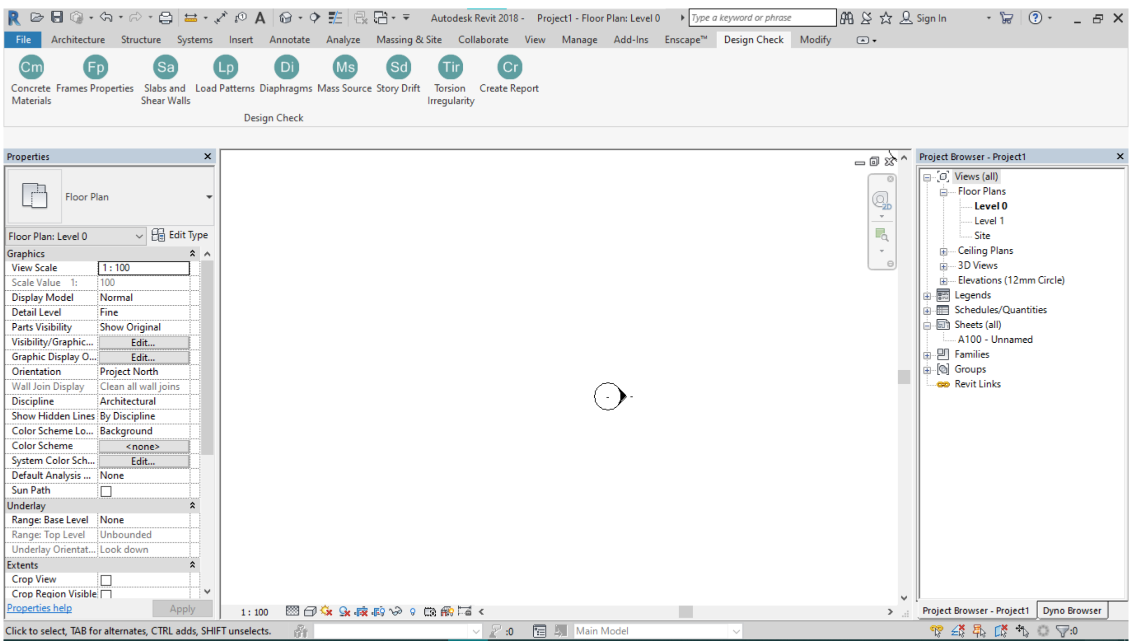


Figure 4.1 Design Check

4.2 Structural Checks

To perform the structural checks, different buttons were created, with each button performing a specific structural check. The results of each of the structural checks can be seen by just clicking on the button.

4.2.1 Concrete Materials

The "Concrete Materials" button will show the given name, assigned strength, the strain at maximum strength, the ultimate unconfined strain capacity of all the concrete materials defined when creating the structural model, as shown in Figure 4.2. It will also show whether the concrete defined is lightweight or not.

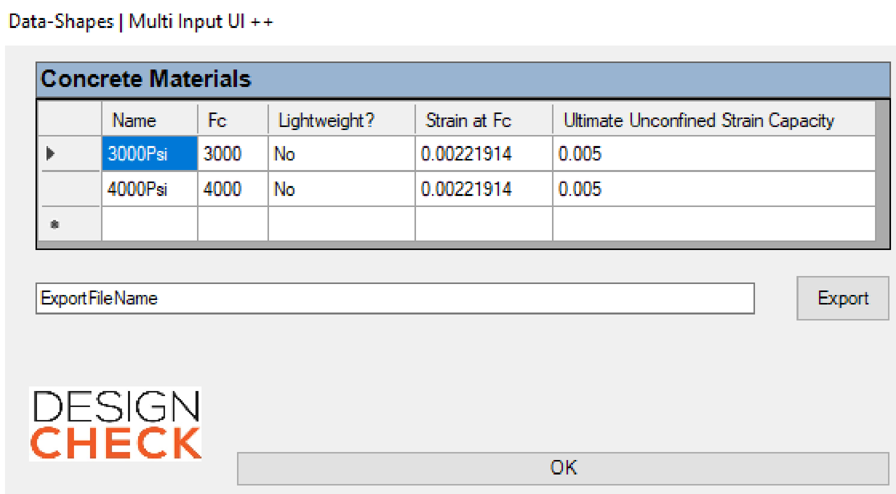
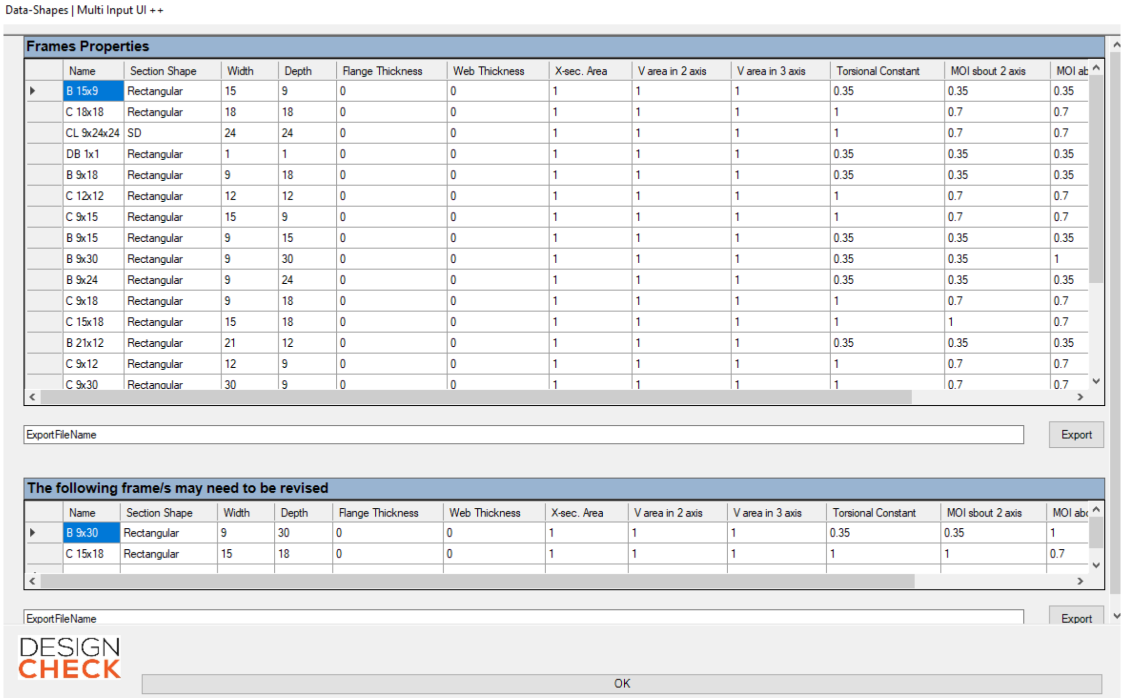


Figure 4.2 Concrete Materials Results

4.2.2 Frames Properties

The "Frames Properties" button will show a list of all the defined frame members (beams and columns), along with their chosen dimensions, and the assigned modifiers. On the bottom, it will show a list of all those frame/s members whose assigned modifiers are non-compliant with the code and that need to be revised. The lists are shown in Figure 4.3.



Data-Shapes | Multi Input UI ++

Frames Properties

Name	Section Shape	Width	Depth	Flange Thickness	Web Thickness	X-sec. Area	V area in 2 axis	V area in 3 axis	Torsional Constant	MOI sbout 2 axis	MOI ab
B 15x9	Rectangular	15	9	0	0	1	1	1	0.35	0.35	0.35
C 18x18	Rectangular	18	18	0	0	1	1	1	1	0.7	0.7
CL 9x24x24	SD	24	24	0	0	1	1	1	1	0.7	0.7
DB 1x1	Rectangular	1	1	0	0	1	1	1	0.35	0.35	0.35
B 9x18	Rectangular	9	18	0	0	1	1	1	0.35	0.35	0.35
C 12x12	Rectangular	12	12	0	0	1	1	1	1	0.7	0.7
C 9x15	Rectangular	15	9	0	0	1	1	1	1	0.7	0.7
B 9x15	Rectangular	9	15	0	0	1	1	1	0.35	0.35	0.35
B 9x30	Rectangular	9	30	0	0	1	1	1	0.35	0.35	1
B 9x24	Rectangular	9	24	0	0	1	1	1	0.35	0.35	0.35
C 9x18	Rectangular	9	18	0	0	1	1	1	1	0.7	0.7
C 15x18	Rectangular	15	18	0	0	1	1	1	1	1	0.7
B 21x12	Rectangular	21	12	0	0	1	1	1	0.35	0.35	0.35
C 9x12	Rectangular	12	9	0	0	1	1	1	1	0.7	0.7
C 9x30	Rectangular	30	9	0	0	1	1	1	1	0.7	0.7

ExportFileName Export

The following frame/s may need to be revised

Name	Section Shape	Width	Depth	Flange Thickness	Web Thickness	X-sec. Area	V area in 2 axis	V area in 3 axis	Torsional Constant	MOI sbout 2 axis	MOI abo
B 9x30	Rectangular	9	30	0	0	1	1	1	0.35	0.35	1
C 15x18	Rectangular	15	18	0	0	1	1	1	1	1	0.7

ExportFileName Export

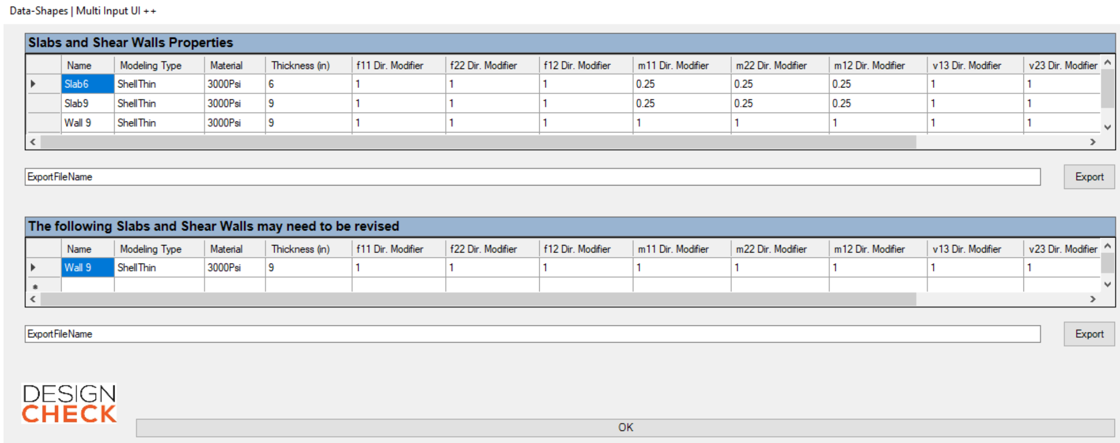
DESIGN CHECK

OK

Figure 4.3 Frames Properties Results

4.2.3 Slabs and Shear Walls Properties

The “Slabs and Shear Walls Properties” button is similar to the “Frames Properties”. It will show a list of all the defined slabs and shear walls, their modeling type, the concrete material for the respective slab and shear wall, the thickness and the assigned modifiers. On the bottom, it will show a list of all those slab/s and/or shear wall/s whose assigned modifiers are non-compliant with the code and that need to be revised. The lists are shown in Figure 4.4.



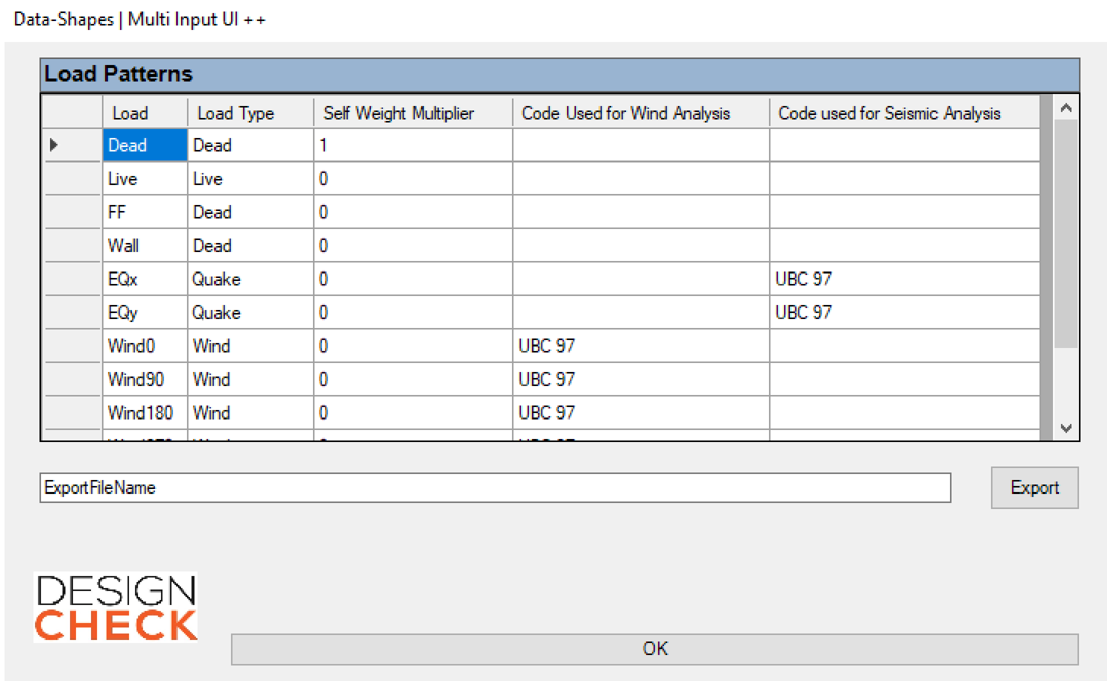
Name	Modeling Type	Material	Thickness (in)	f11 Dir. Modifier	f22 Dir. Modifier	f12 Dir. Modifier	m11 Dir. Modifier	m22 Dir. Modifier	m12 Dir. Modifier	v13 Dir. Modifier	v23 Dir. Modifier
Slab6	ShellThin	3000Psi	6	1	1	1	0.25	0.25	0.25	1	1
Slab9	ShellThin	3000Psi	9	1	1	1	0.25	0.25	0.25	1	1
Wall 9	ShellThin	3000Psi	9	1	1	1	1	1	1	1	1

Name	Modeling Type	Material	Thickness (in)	f11 Dir. Modifier	f22 Dir. Modifier	f12 Dir. Modifier	m11 Dir. Modifier	m22 Dir. Modifier	m12 Dir. Modifier	v13 Dir. Modifier	v23 Dir. Modifier
Wall 9	ShellThin	3000Psi	9	1	1	1	1	1	1	1	1

Figure 4.4 Slabs and Shear Walls Properties Results

4.2.4 Load Patterns

The “Load Patterns” button will show a list of all the loads used for the structural model. It will show the load type, the self-weight factor and the code used for wind and seismic analysis. The results are displayed in Figure 4.5.



Load	Load Type	Self Weight Multiplier	Code Used for Wind Analysis	Code used for Seismic Analysis
Dead	Dead	1		
Live	Live	0		
FF	Dead	0		
Wall	Dead	0		
EQx	Quake	0		UBC 97
EQy	Quake	0		UBC 97
Wind0	Wind	0	UBC 97	
Wind90	Wind	0	UBC 97	
Wind180	Wind	0	UBC 97	

Figure 4.5 Load Patterns Results

4.2.5 Diaphragms

The "Diaphragms" button will show the diaphragms defined, along with the rigidity chosen, as shown in Figure 4.6.

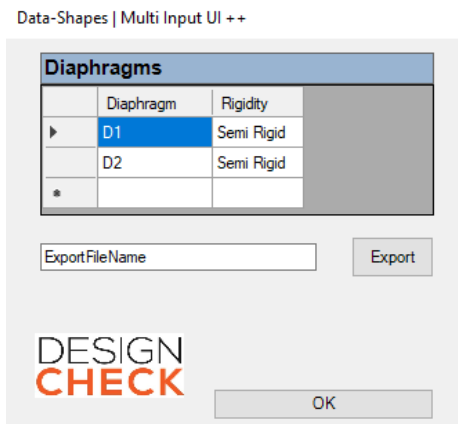


Figure 4.6 Diaphragms Results

4.2.6 Mass Source

The "Mass Source" button will show whether the options for element self-mass, additional mass, specified load pattern in the structural model are checked or unchecked. It will also show the number of load patterns, along with their assigned multiplier. The results are shown in Figure 4.7.

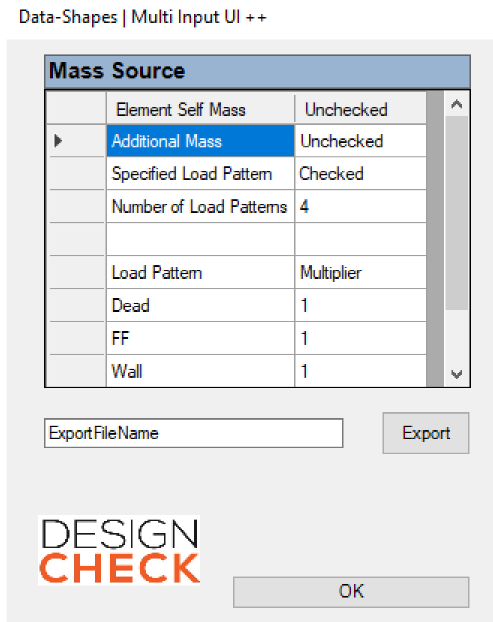


Figure 4.7 Mass Source Results

4.2.7 Story Drift

The "Story Drift" button will first pop up a window asking to enter the deflection amplification factor, the importance factor and the allowable drift (drift limit), as shown in Figure 4.8. These values vary according to the location of the building. However, the values for a building in normal conditions will be there by default. The calculations will be based on these values. The next window will show whether each of the stories is safe or not, as shown in Figure 4.9. This will be shown for both the x and y-axis.

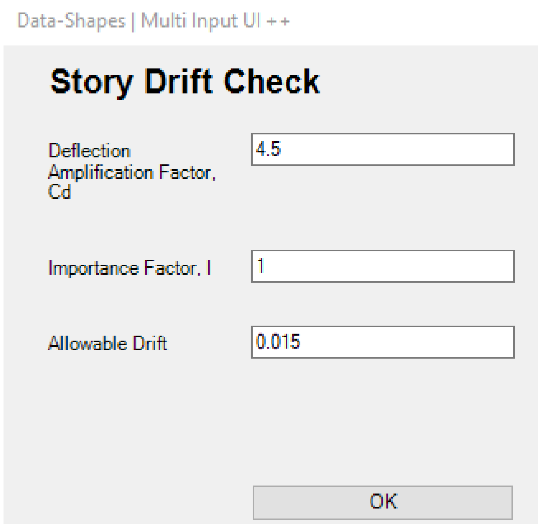


Figure 4.8 Story Drift Check Results (a)

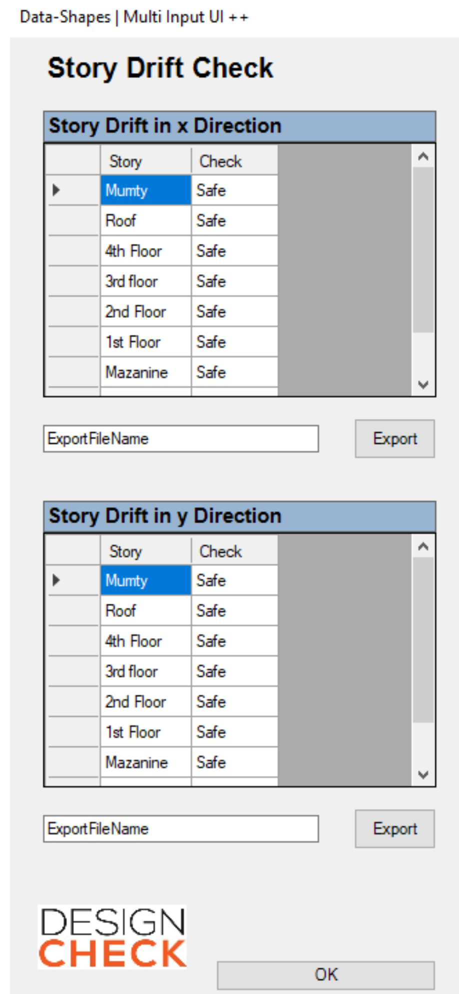


Figure 4.9 Story Drift Check Results (b)

4.2.8 Torsion Irregularity

The “Torsion Irregularity” button will show whether each of the stories is safe or not. If a story is not safe, it will then show whether extreme torsion irregularity exists or not. This is shown in Figure 4.10.

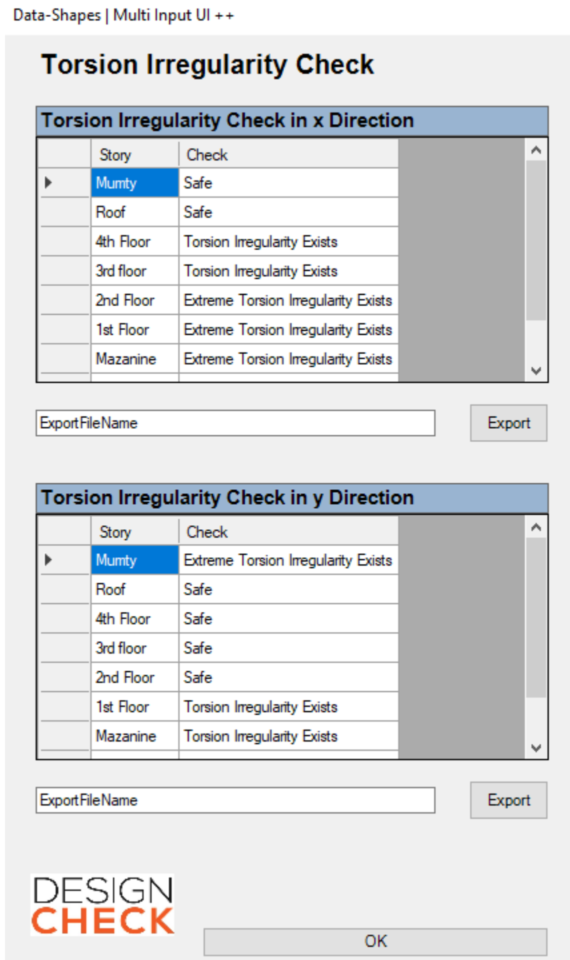


Figure 4.10 Torsion Irregularity Check Results

4.2.9 Create Report

The "Create Report" button creates a report in PDF format. It first asks to choose a folder to save the report in (Figure 4.11). After choosing the folder, the report will be saved in it, along with the results of all the structural checks (Figure 4.12).

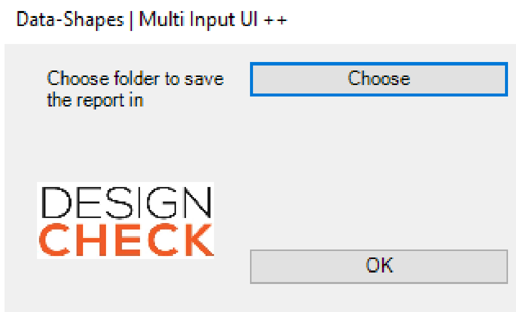


Figure 4.11 Create Report (a)

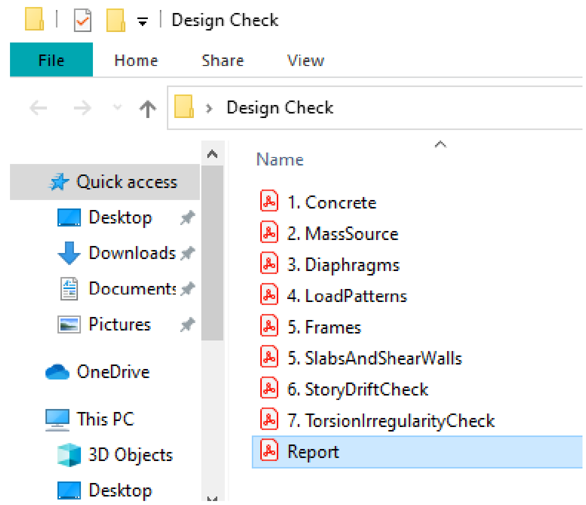


Figure 4.12 Create Report (b)

4.3 Comparison between Manual and Automated Process

This segment compares the manual process with the automated process. The time decreased using the automated process is obvious.

4.3.1 Stiffness Modifiers for Frames, Slabs and Shear Walls

Applying stiffness modifiers can be an iterative process (Wong, et al., 2016). During the structural design vetting process, the engineer has to manually open up three dialogue boxes in order to check the stiffness modifiers of just one frame member (shown in Figure 4.13). Meaning that if there are fifty frame members, the process is to be repeated fifty times. But with “Design Check”, with just one click of a button, all the frame members will be checked and all the non-compliant frame members will be displayed. The same is the case with slabs and shear walls.

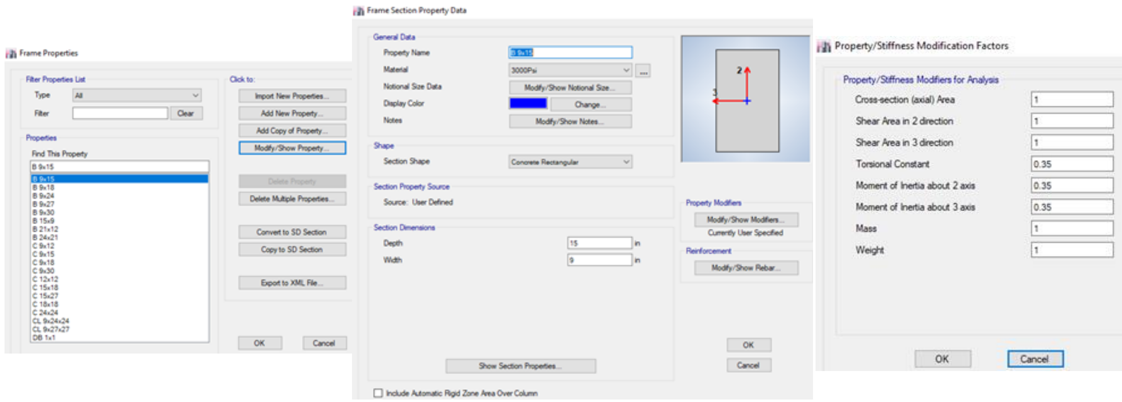
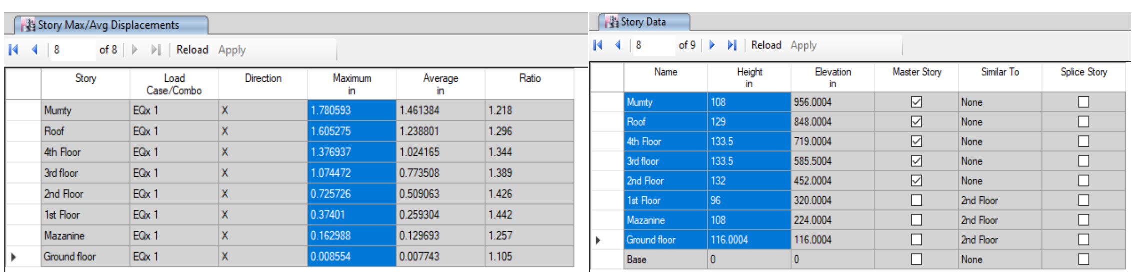


Figure 4.13 Manual Method of Assigning Modifiers

4.3.2 Story Drift Check

In order to perform the story drift check, the engineer extracts the analysis results by opening up different tables in the structural designing software and then copies the relevant results from there (shown in Figure 4.14) and pastes them in Microsoft Excel. After all the relevant data is pasted in Microsoft Excel, the engineer then performs the calculations as given in the code and gets the results. Then finally, the engineer sees whether the structure is safe or not. But with "Design Check", with just one click, we can know whether the structure is safe or not.



Story Max/Avg Displacements

Story	Load Case/Combo	Direction	Maximum in	Average in	Ratio
Mumty	EQx 1	X	1.780593	1.461384	1.218
Roof	EQx 1	X	1.605275	1.238801	1.296
4th Floor	EQx 1	X	1.376937	1.024165	1.344
3rd floor	EQx 1	X	1.074472	0.773508	1.389
2nd Floor	EQx 1	X	0.725726	0.509063	1.426
1st Floor	EQx 1	X	0.37401	0.259304	1.442
Mazanine	EQx 1	X	0.162988	0.129693	1.257
Ground floor	EQx 1	X	0.008554	0.007743	1.105

Story Data

Name	Height in	Elevation in	Master Story	Similar To	Splice Story
Mumty	108	956.0004	☑	None	☐
Roof	129	848.0004	☑	None	☐
4th Floor	133.5	719.0004	☑	None	☐
3rd floor	133.5	585.5004	☑	None	☐
2nd Floor	132	452.0004	☑	None	☐
1st Floor	96	320.0004	☐	2nd Floor	☐
Mazanine	108	224.0004	☐	2nd Floor	☐
Ground floor	116.0004	116.0004	☐	2nd Floor	☐
Base	0	0	☐	None	☐

Figure 4.14 Manual Method of Performing Story Drift Check

4.3.3 Torsion Irregularity Check

This is similar to story drift check as it is also a safety check. The engineer extracts different analysis results and pastes them into Microsoft Excel. The calculations are then performed and then the engineer sees whether the structure is safe or not. "Design

Check” does all this with a click of a button and it is known whether the structure is safe or not.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The architecture, engineering and construction industry is constantly under pressure to produce work faster, at a lower cost and with higher quality. To achieve these goals, the construction industry is becoming increasingly digitalized, with the adoption of BIM, internet technologies and other information technologies (Sandberg, et al., 2016). All of these goals were achieved through the development of the Autodesk Revit plugin. It demonstrates how the automation process works faster, at a lower cost and with higher quality. As a result, this process should be used in the structural design vetting process.

The Plugin can also be used easily among the stakeholders to automatically check the design by themselves before it is forwarded to other stakeholders. It reduces the iterative process of rule checking. Also, the results are saved and can be accessed at any time in the future.

BIM's future is both exciting and challenging. It is emerging as an innovative way to carry out the responsibilities as the way infrastructure projects are designed and built is constantly changing. As more structural and architectural firms recognize the opportunities, benefits and values that it provides, it will continue to transform the industry (Hunt, 2013). This project shows just a fraction of the benefits that can be achieved by utilizing BIM in the structural engineering field.

The automated rule-checking applications should not be viewed solely as agents of the transition to digital administrative processes. Indeed, these applications should be viewed as expert systems that can assist designers by providing a multidisciplinary, informed and detailed view of the implications of their design choices (Martins, Rangel, & Abrantes, 2016).

5.2 Recommendations

This study aimed at automating the structural code compliance process. Following are some of the recommendations that can help improve the work.

- This project included some of the structural checks mentioned in ACI 318 and ASCE 7 and all the structural checks in the codes were not executed. One can study the work in this project, develop an understanding and apply more structural checks mentioned in the codes.
- Furthermore, the project was based on ACI 318 and ASCE 7. However, the work can be replicated by using any other applicable structural code, depending upon country to country.
- In order to make a created plugin or a tool easily accessible, that plugin or tool can be published on the Autodesk App Store, so that anyone can download and benefit from it.
- This project used the structural designing software, ETABS. However, any other software may be used, depending upon the designing firm and their go-to designing software.

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