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ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EFFICTIVE AUTOMATED DESIGN OF BUILDING MODELS FOR TORSIONAL FLEXIBILITY AND LATERAL STABILITY

A Thesis in STRUCTURAL ENGINEERING

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The undersigned have examined the thesis entitled '**Effective Automated Design of Building Models for Torsional Flexibility and Lateral Stability**' presented by **Kirubel Hailegeorgis**, a candidate for the degree of **Master of Science in Civil Engineering (Structural)** and hereby certify that it is worthy of acceptance.

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I certify that research work titled "Effective Automated Design of Building Models for Torsional Flexibility and Lateral Stability" 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

Despite making rapid progress in the field of earthquake science, seismologists are still unable to forecast the occurrence of the big one. Earthquake forces are unpredictable by nature, and sophisticated analysis and design options cannot guarantee complete safety of a structure against an earthquake. Therefore, current and emerging design philosophies require regularity to be one of the main considerations when designing a structure. Regular structures are capable of withstanding earthquake forces much better than irregular structures. Torsional regularity is the most important criterion for determining regularity of a structure. The drift sensitivity coefficient (θ), a parameter that describes stability of a structure, is another parameter that needs due attention during design of buildings.

However, calculating parameters that describe both torsional regularity and stability of a structure can be very tedious. For this reason, structural designers often tend to create approximate methods of calculating these parameters. Nonetheless, these parameters are of great importance, therefore it is essential to avoid using approximate methods and results. Moreover, it is a common trend to increase the cost of the structure just so that calculation of these parameters is omitted.

To address these problems, a software program that can calculate these parameters effortlessly is developed. This program, unlike the conventional approach, is also capable of solving stability and torsional rigidity issues simultaneously. With the use of parametric data, the program is capable of suggesting strategic wall locations and making the necessary structural modifications that can address both issues. This approach prevents worsening of torsional rigidity behaviour while taking structural measures for solving stability issues, eliminating the need for excessive usage of structural members like walls.

The software interacts with conventional structural design software to extract required data, to analyze status, detect problems and suggests solutions to create a sound structural system. Through the developed graphical user interface, the solutions are reported to the user, and capability of applying the solutions automatically is one of the features of the program. The program employs fuzzy logic to determine depth of detected problem, aiding designers foresee extent of required structural modifications. Proper functioning of the program is verified by replicating an example done by Eurocode designers guide.

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TABLE OF CONTENTS

ABSTRACT .... **IV**

ACKNOWLEDGMENTS .... **V**

TABLE OF CONTENTS .... **VI**

LIST OF TABLES .... **IX**

LIST OF FIGURES .... **XI**

CHAPTER 1 INTRODUCTION **1**

1.1 Background 1
1.2 Research Objectives 3
1.2.1 General Objective 3
1.2.2 Specific Objective 4
1.3 Scope of the Study 4
1.4 Significance of the Study 5
1.5 Research Methodology 6
1.5.1 Research design 6
1.5.2 Software development 6
1.5.3 Data collection 7
1.5.4 Data analysis 7
1.5.5 Verification 7

CHAPTER 2 LITRATURE REVIEW **8**

2.1 Torsional rigidity of structures 8
2.1.1 Factors affecting torsional flexibility of concrete structures: 9
2.1.2 Performance enhancement of torsional flexible structures 12
2.1.3 Measurement of Torsional Rigidity 13
2.2 Lateral Stability of structures 14
2.2.1 Material Properties 15
2.2.2 Reinforcement 17
2.2.3 Geometry 18

2.2.4 Loading Conditions 18
2.2.5 Modelling and Analysis 19
2.2.6 Design Codes and Standards 21
2.2.7 Summary of factors affecting lateral stability 22
2.3 Fuzzy logic and Building Problem Assessment 22
2.4 Previous studies on related topics 24
CHAPTER 3 PROGRAM DESIGN AND IMPLEMENTATION 26
3.1 Introduction 26
3.2 Program Flow Chart 27
3.2.1 Flow chart for Stability Analysis 27
3.2.2 Flow chart for Torsional Rigidity Check 29
3.2.3 Flow chart for Stability and Torsional Rigidity Design 31
3.2.4 Flow chart for Model Automation 33
3.3 Program Structure Design 34
3.3.1 Stability Analysis 34
3.3.2 Torsional Rigidity Check 35
3.3.3 Analysis and Design Integration 35
3.3.4 Model Automation 35
3.3.5 Graphical User Interface 36
3.3.6 Object Oriented Programming 36
3.4 Implementation details and methods 37
3.4.1 Programming Language 37
3.4.2 Tkinter Library 37
3.4.3 ETABS API Integration 38
3.4.4 Coding Practices 38
3.4.5 Testing Techniques 38
3.4.6 Challenges Encountered 38
CHAPTER 4 USER INTERFACE AND DATA REQUIREMENT 40

4.1 Introduction 40
4.2 Stability Analysis 42
4.3 Torsional Rigidity Analysis 45
4.4 Integrated Design of Lateral Stability and Torsional Rigidity 48
4.5 Model Automation 51
4.5.1 Add Walls 51
4.5.2 Remove Walls 52
4.5.3 Change Thickness of Wall 53
CHAPTER 5 VERIFICATION AND DESIGN EXAMPLE 56
5.1 Analysis and Design Example 56
5.1.1 Analysis 57
5.1.2 Design 94
5.2 Verification based on Eurocode 8: Worked Example 101
5.2.1 Modelling 101
5.2.2 Program analysis 103
5.3 Results and Comparison 109
CHAPTER 6 FUZZY LOGIC-BASED BUILDING ASSESSMENT 111
6.1 Fuzzification 111
6.1.1 Crisp inputs in to the system 111
6.1.2 Membership functions 112
6.2 Inference 115
6.3 Defuzzification 116
CHAPTER 7 CONCLUSIONS AND RECCOMENDATIONS 118
7.1 Conclusions 118
7.2 Recommendations 118
REFERENCES 115
APPENDIX 119

LIST OF TABLES

Table 5-1 X-Max drift results 62

Table 5-2 X-Max story forces 63

Table 5-3 θ_X (Max) for all combinations 64

Table 5-4 θ_X (Max) governing values for each storey 65

Table 5-5 X-Min drift results 66

Table 5-6 X-Min story forces 66

Table 5-7 θ_X (Min) for all combinations 67

Table 5-8 θ_X (Min) governing values for each storey 68

Table 5-9 Y-Max drift results 69

Table 5-10 Y-Max story forces 69

Table 5-11 θ_y (Max) for all combinations 70

Table 5-12 θ_y (Max) governing values for each storey 71

Table 5-13 Y-Min drift results 72

Table 5-14 Y-Min story forces 72

Table 5-15 θ_y (Min) for all combinations 73

Table 5-16 θ_y (Min) governing values for each storey 74

Table 5-17 Comparison on stability analysis results (X-direction) 78

Table 5-18 Comparison on stability analysis results (Y-direction) 79

Table 5-19 Center of mass and Center of stiffness 80

Table 5-20 Defined load cases 81

Table 5-21 Point object definition 82

Table 5-22 Summary of torsional radius (r_y) 87

Table 5-23 Summary of torsional radius (r_x) 88

Table 5-24 Summary of Eccentricity-X 89

Table 5-25 Summary of Eccentricity-Y 90

Table 5-26 Comparison for Eccentricity results 93

Table 5-27 Comparison for Torsional radius results 94

Table 5-28 Summary of results (r_x) 108

Table 5-29 Summary of results (r_y) 109

Table 5-30 Summary of comparisons (r_x) 110

Table 5-31 Summary of comparisons (r_y) 110

Table 6-1 Fuzzified values for each parameter 115

Table 6-2 Results of the inference system 115

LIST OF FIGURES

Figure 2-1 Maximum and Minimum deflections of a torsionally flexible structure. [7] ... 8

Figure 2-2 (a) Eccentric Structure System. (a) Regular Structure System [2] 11

Figure 3-1 Flow chart for Stability Analysis 28

Figure 3-2 Flow chart for Torsional Rigidity Check 30

Figure 3-3 Flow chart for Stability and Torsional Rigidity Design................................. 32

Figure 3-4 Flow chart for Model Automation 33

Figure 4-1 Tab System of the GUI 41

Figure 4-2 Stability Analysis input window.. 42

Figure 4-3 X-Direction Maximum stability data 43

Figure 4-4 X-Direction Minimum stability data.. 44

Figure 4-5 Y-Direction Maximum stability data 44

Figure 4-6 Y-Direction Minimum stability data.. 44

Figure 4-7 Stability Analysis input window.. 45

Figure 4-8 X-Direction Torsional Rigidity data 47

Figure 4-9 Y-Direction Torsional Rigidity data 48

Figure 4-10 Integrated Design of Lateral Stability and Torsional Rigidity input window 49

Figure 4-11 Problem Identification and Suggested Solutions 50

Figure 4-12 Input window for Adding Wall into the building model 51

Figure 4-13 Input window for Removing Wall from the building model 52

Figure 4-14 Input Window for Defining a New Section to Change Thickness of Wall ..54

Figure 4-15 Input Window for Using an Existing Section to Change Thickness of Wall55

Figure 5-1 3D Architectural Representations 58

Figure 5-2 3D Structural Representation 58

Figure 5-3 Elastic RSM spectrum...60

Figure 5-4 Design RSM spectrum 60

Figure 5-5 Input data for torsional stability analysis 75

Figure 5-6 Stability analysis results from the program (X-Max) 75

Figure 5-7 Stability analysis results from the program (X-Min)......................................76

Figure 5-8 Stability analysis results from the program (Y-Max) 76

Figure 5-9 Stability analysis results from the program (Y-Min)......................................77

Figure 5-10 Input data for torsional radius calculation 91

Figure 5-11 Torsion analysis results from the program (X-direction) 91

Figure 5-12 Torsion analysis results from the program (Y-direction) 92

Figure 5-13 Input data for the design of the building...96

Figure 5-14 Identified problems 97

Figure 5-15 Program generated solutions..98

Figure 5-16 Stability design results from the program (X-Max)......................................98

Figure 5-17 Stability design results from the program (X-Min) 99

Figure 5-18 Stability design results from the program (Y-Max)......................................99

Figure 5-19 Stability design results from the program (Y-Min) 100

Figure 5-20 Torsional rigidity design results from the program (X-Direction) 100

Figure 5-21 Torsional rigidity design results from the program (Y-Direction) 101

Figure 5-22 3D Model of the example building. 102

Figure 5-23 Input data for the case of Model Type 1 104

Figure 5-24 Y-direction results for Model type 1...104

Figure 5-25 Y-direction results for Model type 1...104

Figure 5-26 Input data for the case of Model Type 2 105

Figure 5-27 X-direction results for Model type 2...106

Figure 5-28 Y-direction results for Model type 2...106

Figure 5-29 Input data for the case of Model Type 3 107

Figure 5-30 X-direction results for Model type 3...107

Figure 5-31 Y-direction results for Model type 3...108

Figure 6-1 Membership functions 114

Figure 6-2 Chopped off output membership function 116

Figure 6-3 Crisp output value..117

CHAPTER 1 INTRODUCTION

1.1 Background

Excessive torsional behaviour of asymmetric building structures is observed to be the main cause of the poor seismic performance. [1] Torsion in structures subjected to lateral loads is caused by the disparity between the locations of the center of mass and the center of rigidity. Between the center of mass and the center of rigidity, there may be an eccentricity due to concrete walls, slab holes, overhangs, column clouds, etc. When a structure is under torsion, lateral deflections increase in the weak direction and decrease in the strong direction. As a result, some particular structural members would be subject to greater ductility demands. Increased lateral displacement would also increase the likelihood of impacting nearby structures.

Past earthquake disasters show that rigid structural system elements do not mean earthquake resistant structural system. An earthquake resistant building should be free from structural irregularities. [2]

Buildings should be designed, in accordance with Eurocode 8, to reduce the consequences of torsional irregularity during seismic events. The code encourages designers to seek for a structure that is regular in plan by imposing a lower value of behaviour factor. Torsional stiffness is one of the essential criteria for a structure to be classified as regular in plan.

Eurocode 8 section 4.2.3.2(6) states that, at each level and for each direction of analysis x and y, the structural eccentricity e_o and the torsional radius r shall be in accordance with the two conditions below, which are expressed for the direction of analysis y: [3]

$$e_{ox} \leq 0.30 \times r_x \quad (1\text{-}1)$$

$$l_s \leq r_x \quad (1\text{-}2)$$

where:

e_{ox} is the distance between the center of stiffness and the center of mass, measured along the x direction, which is normal to the direction of analysis considered

r_x is the square root of the ratio of the torsional stiffness to the lateral stiffness in the y direction ("torsional radius"); and

l_s is the radius of gyration of the floor mass in plan (square root of the ratio of the polar moment of inertia of the floor mass in plan to the area of the floor mass)

Story Drift is defined as the difference in lateral deflection between two adjacent stories. [4] The sideways or lateral displacement between two adjacent story can also be used to describe it. The second order effects will grow as the story drift does. Additionally, the plot will go off course if second order effects are enhanced. This brings up the issue of structural stability. The stability system is the combination of elements, that keep the building standing against these lateral forces. [5] Story drift must be kept to a minimum or the structure will become unstable.

Eurocode 8 section 4.4.2.2(2) demands this stability issue to be treated by limiting the inter story drift sensitivity coefficient which is calculated as follows. [3]

$$\theta = \frac{p_{tot} \times d_r}{V_{tot} \times h} \tag{1-3}$$

where:

θ is the inter story drift sensitivity coefficient

p_{tot} is the total gravity load at and above the storey considered in the seismic design situation.

d_r is the design inter story drift, evaluated as the difference between the average lateral displacement (d_s) at the top and bottom of the storey under consideration.

V_{tot} is the total seismic story shear.

h is the inter story height.

Unfortunately, these stability and torsional rigidity checks for multistorey buildings are very time consuming and prone to computational errors. For this reason, structural engineers often use other simpler but not exact alternative methods of calculation.

Furthermore, for efficient structural design, torsional rigidity and stability checks must be done simultaneously. However, the trend amongst current practicians is to treat them separately i.e., stability checks are first done and required structural measures taken (usually addition of structural walls). After that, the problem of torsional flexibility is treated, usually involving the addition of more structural walls. This would ultimately be the reason for uneconomical design of buildings.

This research paper aims to solve both stated issues by developing a software that is capable of making the torsional rigidity and stability checks effortless. Both parameters will also be inspected at the same time and structural measures that favours enhancement of both structural parameters will be taken resulting an efficient design.

1.2 Research Objectives

1.2.1 General Objective

Developing a program that is capable of creating cost effective, torsionally rigid and stable models. Structures designed using the software are more efficient and cost effective as compared to structures designed without the application of this software. This is because of the fact that, the software is designed in such a way that it addresses stability and torsional flexibility problems in parallel. The software will also be capable of determining drift sensitivity coefficient and check torsional regularity effortlessly.

1.2.2 Specific Objective

- Writing a program that is capable of extracting results from structural analysis software and determine drift sensitivity coefficient.
- Writing a program that is capable of extracting results from structural analysis software and determine torsional regularity of the structure.
- Extending the code so that it can give the user sets of solutions that can solve both stability and torsional flexibility problems at the same time. These structural solutions will be available whenever the calculated parameters are not in accordance with the design code. The depth of required modifications will also be estimated through the application of fuzzy logic.
- Enabling the program to automatically create torsionally rigid and stable model by applying the suggested solutions.
- Developing a program with a user interface for structural designers to be able to use the above stated functionalities and get summarized results.

1.3 Scope of the Study

This paper is limited to developing a program that can design building structures for stability and torsional rigidity based on Eurocode-8 regulations. The program is designed to have a user interface where by the user can enquire for the intended calculations and get a detailed result of the requested parameters. Along with the report, the program also gives alternative solutions that can solve both torsional flexibility and lateral stability issues whenever these parameters are outside the limits stated by the code. Furthermore, the program is capable of executing the suggested solutions automatically to create a torsionally rigid and stable model.

1.4 Significance of the Study

To ensure that structural designs are efficient and cost-effective, it is necessary to conduct both stability and torsional rigidity checks simultaneously. However, the nature of computational work involved in verifying the stability and torsional rigidity of building structures makes it impossible to treat them both at the same time. Current trend among practitioners of the field is to treat them separately.

In today's practice, the first step is to perform lateral stability checks. If the model falls outside of the acceptable limits set by the design code, appropriate structural measures are taken, usually involving the addition of structural walls or strengthening of existing ones. However, during the process of adding or strengthening walls, there is no parametric data available that can express the torsional flexibility characteristics of the model. This makes the placement of structural walls or the selection of walls to be stiffened less strategic. In the second step, structural designers check the torsional flexibility of the structure, which usually involves adding more structural walls to the system, making the overall design more expensive. This paper aims to solve this problem by treating both parameters simultaneously.

For structural designers, determining the regularity of floors in multi-story plans is an iterative, laborious and time-consuming procedure. As a result, this process is frequently carried out with lower quality. Many structural designers choose to use behaviour factor values that are lower than necessary and skip checking the building's plan regularity. This increases the overall cost of the structure. Moreover, the iterative and laborious work involved in checking regularity discourages designers from striving for a regular structure, which is much better equipped to withstand unpredictable earthquake forces. With the program, designing structures for torsional rigidity involves much lesser iterations because of the objective (parametric data usage) approach followed and the application of fuzzy logic to determine the size of required structural solution.

Structural Engineers were forced to come up with a different plan of action due to the time-consuming work necessary for drift and stability check. Many designers currently calculate the drift sensitivity coefficient for a single combination that gathers the maximum and minimum values of all combinations (design envelope). This approach, even though sounds correct, provides a lower bound value for the drift sensitivity coefficient. Underestimated values of drift sensitivity coefficient make the design of structures for lateral loads ill conditioned.

In pursuit of solving the above-stated problems, this paper aims to provide a software that will make determining the drift sensitivity coefficient and checking torsional regularity effortless. Furthermore, the software will be programmed to find a stable arrangement of structural members and create seismic-resistant models automatically.

1.5 Research Methodology

1.5.1 Research design

For the development of the software, Python programming language is used. Different modules that target specific tasks are developed and then integrated in another module. Application Programming Interface (API) is used to interact with the structural design software for data gathering and making structural innervations. An executable software with a user interface that is to be utilized by the user for data enquiry and data extraction is also developed as a front end for the program.

1.5.2 Software development

Program is written to calculate drift sensitivity coefficient and to check for torsional regularity. API is used to extract the raw data needed for the calculation from ETABS. Another set of code are then written to capacitate the program so that it can detect major structural problems if there are any. API is once again used to make structural intervention on the model to solve the detected problems. While solving the structural problems, both stability and torsional rigidity are considered and multiple solutions that favours both parameters are proposed by the program. All the above stated program modules are then integrated into an executable that have its own user interface to ask information from the user and deliver results back to the user.

1.5.3 Data collection

API programming technique is used to extract analysis results like storey forces, drift and model dimensional parameters in a comma separated format. Furthermore, data from the user is used for the required analysis. The user feeds in the required information on the spaces provided on the user interface.

1.5.4 Data analysis

Using the collected data, torsional rigidity check and lateral stability check is done by the program. The analysis starts when the user informs the program to do the analysis by clicking on the Run Analysis button available on the user interface. It shall be noted that, provisions of Eurocode-8 are used for the analysis and checking of the analysis results. Form the analysis results and geometric parameters of the model, multiple structural solutions will be developed by the program and presented to the user.

1.5.5 Verification

A building that is proposed to be constructed after design is subjected to both manual and program assisted design for torsional rigidity and lateral stability. Parametric data regarding torsional flexibility and lateral stability are solved for by using both techniques. Comparisons are then made to check the extent to which the program assisted and manual analysis are similar.

The program is also validated by using a trusted document by the title Eurocode 8: Seismic Design of Buildings: Worked examples. A building model described in the document is recreated, and the developed program is used to perform a torsional rigidity check. The results obtained are then compared to those presented in the manual to validate the accuracy of the developed program.

CHAPTER 2 LITRATURE REVIEW

2.1 Torsional rigidity of structures

The ability of a concrete structure to resist torsion or twisting, also known as its torsional rigidity, is a fundamental property that plays a significant role in determining the overall resistance and deformation behaviour of a structure. This property is particularly important when designing concrete structures that are subject to lateral loads, such as those caused by earthquakes or wind, as it directly affects their ability to withstand such loads. The reduction in capacity of structures against imposed lateral loads is attributed to the effect of increased ductility demand. [6] According to the study done by Kyrkos and Anagnostopoulos, elements at the so called "flexible" edges of the buildings exhibit substantially higher ductility demands than elements at the "stiff" edges. [6] Torsional irregularity occurs when the ratio of the largest relative displacement in each of the floors in the earthquake direction to the average relative displacement of the same floor is greater than 1.2. [7] But it is very costly and unrealistic for concrete structures to possess the required ductility demand.

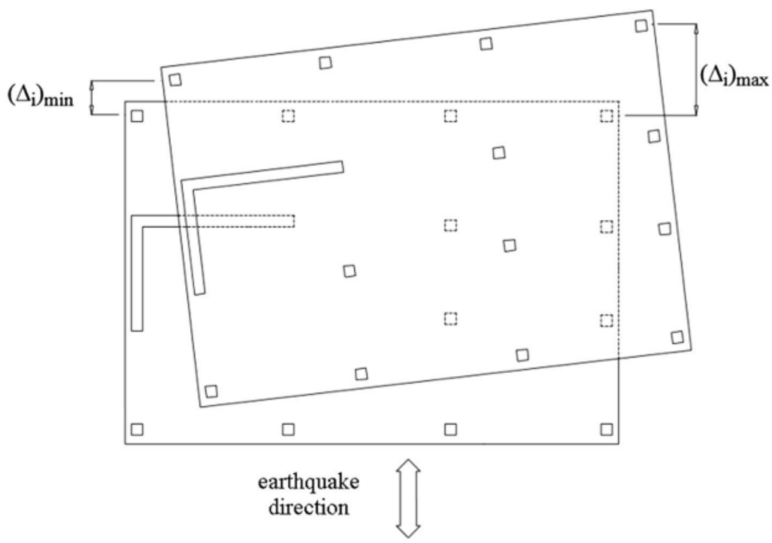


Figure 2-1 Maximum and Minimum deflections of a torsionally flexible structure. [7]

Concrete structures' torsional stiffness is a complicated attribute that is controlled by a number of variables. These variables include the size and shape of the structure's cross-section, the placement of the reinforcement, the kind and intensity of the applied loads. In addition, other factors like the characteristics of the concrete used and the quality of the analysis methodologies used to calculate the structure's torsional rigidity may also have a substantial impact on how the structure behaves globally.

It is obvious that in the design and evaluation of concrete structures torsional rigidity is a critical parameter that cannot be ignored. In order to improve our understanding of the numerous factors that affect this parameter and to come up with more precise analysis tools that can be used to evaluate the torsional stiffness of concrete buildings, further studies must be done. By doing so, one can make sure that concrete structures are designed to be more durable and capable of withstanding the lateral loads they may be subjected to.

2.1.1 Factors affecting torsional flexibility of concrete structures:

2.1.1.1 Irregular mass distribution

Plan irregularity in mass distribution can cause torsional flexible structures by affecting the distribution of lateral loads throughout the structure specifically during an earthquake event. When a structure is subjected to an earthquake, the applied load is a function of the mass of the structure. If the mass of the structure is not uniformly distributed, the seismic action will also be non-uniform load this can twist or rotate the structure around its vertical axis. In other words, if a structure has an irregular mass distribution, it can lead to a non-uniform distribution of lateral loads throughout the structure. Therefore, certain parts of the structure may be subjected to higher lateral loads than others, causing uneven deformation and potential torsional twisting. This can result in structural damage and compromise the overall stability of the structure.

For example, consider a building with an irregular mass distribution due to a concentration of mass on one edge of the structure. During an earthquake event, that edge of the building may experience higher lateral loads than the rest of the building due to its big mass, leading to uneven deformation and torsional twisting. This can lead to structural damage and potentially compromise the safety of the building. Infill walls can change the location of center of mass. Therefore, asymmetrically placed walls may cause excessive torsion in structures. Which in turn causes extra shear force on structural elements. [2]

In contrast, a building with a regular mass distribution will distribute lateral loads more evenly throughout the structure, leading to a more uniform deformation and a higher torsional stiffness. Therefore, careful consideration of the mass distribution and plan irregularities is crucial in the design of torsionally rigid structures that can withstand lateral loads.

2.1.1.2 Irregular stiffness distribution

Stiffness irregularity in plan is a phenomenon where certain areas of a building are stiffer than others, leading to uneven distribution of stiffness in a building's plan. This results in torsional effects on the structure, which can cause it to twist when subjected to lateral loads. Torsional flexibility, which refers to a structure's ability to resist rotational forces around its vertical axis, is directly proportional to the stiffness irregularity and the lateral loads acting on the structure.

Earthquake load acts at the center of mass of the structure. However, resisting force acts at a point called center of rigidity on the structure, which is the center of lateral resistance. Torsional problems take place when the mass center and center of rigidity are not located at the same place. By increasing distance between center of mass and center of rigidity, building is forced to twist around the rigid structural section (rigid core) and subjected to great torsional moments. [2] Careful selection of location of vertical lateral force resisting system so that the center of rigidity of the system coincides with center of mass, significantly decreases torsional effects. [8]

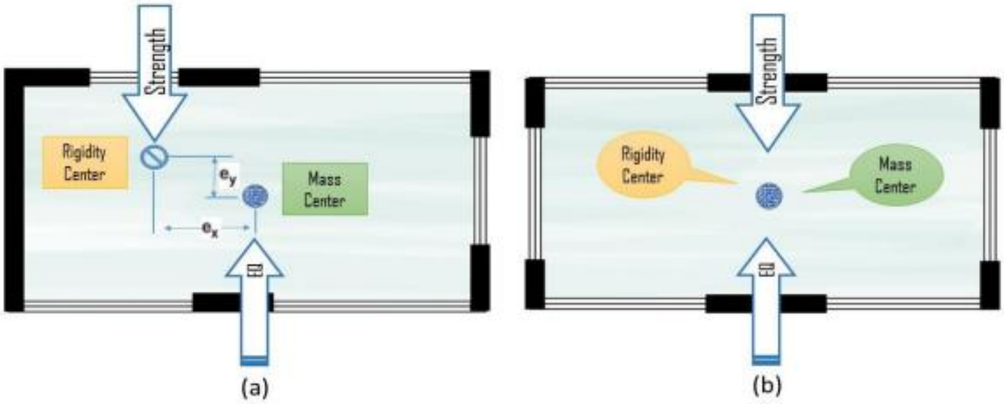


Figure 2-2 (a) Eccentric Structure System. (a) Regular Structure System [2]

To mitigate the effects of stiffness irregularity in plan, structural engineers can adopt various design strategies. Symmetrical floor plans, designing structures with uniform stiffness, and implementing torsional bracing systems are some of the strategies that can be used. Increasing strength of structural elements on the weaker side of the building or decreasing strength of structural elements on the stronger side can prevent effects of torsion on structures. Obviously, the best solution is to design structural systems free from irregularities including torsional irregularity. [2]

2.1.1.3 Planar shape of structures

The performance of a building during earthquakes is affected by the shape and geometry of the building in addition to the effect of earthquake forces acting on it. [9] Hence it is of utmost importance to select a good building configuration at the initial stages itself. It has been noticed that buildings with simple or regular plan geometry suffer lesser damage to earthquake. The challenge for a structural engineer and architect is to be able to create a structurally functional as well as aesthetically appealing building which leads to development of irregular plan buildings.

In this study different plan configurations are considered, namely E-shape, H-shape, plus and swastika shapes were modelled using ETABS v9 software to analyze the performance of different plan shapes. From the obtained results, the following conclusions are made.

- It is seen that variation in plan configuration of the structure affects the displacement and storey drift.
- The swastika shape configuration showed good performance compared to the other models.
- Not only plan configuration but also diaphragm effect affects the behavior of structure.
- In the case of structures with irregularity in plan semi-rigid diaphragm must be considered.

2.1.1.4 Ratio between lateral and torsional stiffness

Discrepancies between the computed and actual values of the structural element stiffness imply that a building with nominally symmetric plan is actually asymmetric to some unknown degree and will undergo torsional vibration when subjected to purely translational ground motion. Such accidental torsion leads to increase in structural element deformations which is shown to be essentially insensitive to the uncoupled lateral vibration period of the system but is affected strongly by the ratio of uncoupled lateral and torsional vibration periods. [10]

The increase in response due to the accidental torsion caused by stiffness uncertainty is relatively insensitive to the uncoupled vibration period of the system. However, this increment is very sensitive to the value of the lateral period to torsional period ratio. This is attributed to the fact that, the response of systems with low lateral to torsional period ratio is not sensitive to the presence of twisting actions. [10]

2.1.2 Performance enhancement of torsional flexible structures

Because of the complex behaviour of such structures under earthquake excitations, it is not surprising that, in spite of the large research efforts in plan irregular building structures dating back to the 1970s, even in recent years, many papers have been devoted to a better understanding of seismic response especially in the inelastic range mainly of simplified one-storey building models. Significant conclusions have been drawn regarding magnitude of rotational response, bi-directional eccentricity and input ground motion, and optimized strength distributions. [11]

When element strength is specified according to code design eccentricity expressions, the element at the stiff edge is the critical element which suffers significantly more severe damage than corresponding symmetric structures. The peak displacement ductility demand of the element at the flexible edge is always lower than that of corresponding symmetric structures. The approach of including accidental eccentricity in the code design eccentricity expressions but ignoring uncertainties and torsional ground motion in inelastic dynamic analysis is misleading if the structure under consideration is torsional flexible. [12]

2.1.3 Measurement of Torsional Rigidity

A fast, simple, and reliable manual calculation method called shear and bending combination method (SBCM) for assessing the torsional stability of the multi-storey building under elastic conditions is readily available. The simple sets of equations derived in SBCM method are useful for buildings with a shear wall, a moment resisting frame, and a dual structural system consisting of horizontal as well as vertical stiffness irregularity. The proposed method determines the torsional stability by quantifying the elastic radius ratio of the building. The accuracy and robustness of the proposed method have been verified through the parametric study consisting of 81 different multi-storey building models. The proposed method predicted the elastic radius ratio of the building within the 5% difference to the static analysis method, a reputed computer analysis method. [13]

Procedures of Determining Elastic Radius Ratio based on the SBCM is presented below.

- Determination of the structural system. The lateral load resisting method for the structure is classified as Shear wall system, Moment resisting System or Dual system.

- Calculate elastic radius ratio due to shear mechanism. The shear mechanism is torsional resistance of an individual shear wall trying to resist torsional moment acting about its vertical axis. For the determination of elastic radius ratio, formulations for each type of lateral load resisting systems are readily available.
- Calculate elastic radius ratio due to bending mechanism about the centre of mass of the system. The bending mechanism is torsional resistance of a system of shear walls trying to resist torsional moment acting about the vertical axis of the building under consideration. For the determination of elastic radius ratio, formulations for each type of lateral load resisting systems are readily available.
- Calculate elastic radius ratio due to bending mechanism about the centre of rigidity of the system. This can be done using the formula that involves eccentricity values and elastic radius ratio about centre of mass.
- Calculate the total elastic radius ratio. This is calculated as the square root of sum of the squares of the two elastic radius ratio values from shear and bending mechanism.

The positioning of the lateral load resisting elements in the building plan is the major factor determining the torsional stiffness of the structure. The torsional stiffness is higher for buildings with walls or frames that are located away from the center of rigidity. The highest elastic radius ratio can be obtained if all walls are located at the building edges or corners. Moreover, a building with wall elements aligned about both principal directions normally is more torsionally stiffer compared to a building with walls aligned in one direction only. [13]

2.2 Lateral Stability of structures

Excessive and uncontrolled lateral displacements can create severe structural problems. Empirical observations and theoretical dynamic response studies have indicated a strong correlation between the magnitude of inter story drift and building damage potential. [14] Ensuring the lateral stability of concrete structures is very important when it comes to guaranteeing the safety and dependability of structures under lateral loads, such as wind, earthquakes, and other forces. The ability of a concrete structure to withstand these types of loads is reliant upon a multitude of factors, including the material properties of the concrete itself, the type and presence of reinforcement used, the structure's geometry and design, the conditions under which the structure is loaded, and the accuracy of the analysis techniques utilized to asse ss the structure's stability.

Given the crucial role of lateral stability in ensuring the structural integrity and safety of concrete structures, it is of utmost importance to delve deeper into the factors that influence it. This literature review aims to provide a comprehensive overview of the existing research on lateral stability of concrete structures and to highlight the key factors that play a critical role in determining their stability.

The investigation of lateral stability in concrete structures has received substantial attention from researchers, engineers, and practitioners all over the world. This literature review aims to provide insights into the latest advancements in the focus area and identify gaps that require attention. Additionally, by discussing the critical factors that impact the lateral stability of concrete structures, this review provides a framework for future research and practice. The framework can enable the development of stronger and more durable concrete structures that can withstand lateral loads caused by wind, earthquakes, and other sources.

2.2.1 Material Properties

Concrete is a composite material that is made up of various constituents such as cement, water, aggregates, and additives which collectively contribute to its strength and rigidity. The compressive strength of concrete is a crucial parameter that significantly influences the overall lateral stability of concrete structures. The ability of a concrete structure to withstand lateral loads, such as wind or seismic forces is directly proportional to its compressive strength. Higher compressive strength means increased resistance to these loads thereby enhancing the stability of the structure. This has been substantiated by different studies, that has demonstrated that the compressive strength of concrete is one of the primary factors that determine the lateral stability of concrete structures.

However, lateral stability of structures could be lesser when high strength concrete is used for the construction of buildings. This is attributed to the fact that high strength concrete would normally allow the use of lesser number of framing members which in turn results in lesser lateral stiffness. [15]

In addition to the compressive strength the modulus of elasticity is also another essential parameter that impacts the lateral stability of concrete structures. Modulus of elasticity is a measure of the material's stiffness. And it also quantifies the relationship between stress and strain. Concrete structures with higher modulus of elasticity tend to be stiffer and less susceptible to deformation when subjected to lateral loads. This characteristic makes them more resilient to lateral loads further improving the overall stability of the structure. According to different literatures, a higher modulus of elasticity results in a more rigid structure, thereby reducing the effects of lateral loads.

It is therefore imperative to consider the compressive strength and modulus of elasticity of concrete while designing and constructing concrete structures. A deep understanding of these properties can help engineers optimize their design and improve the stability of the structure under consideration against lateral loads.

Modulus of Elasticity of concrete can be enhanced by adjusting the mix proportions, increasing the compressive strength, and incorporating stiffer aggregates. Despite the potential benefits of these conventional methods, the resulting concrete often exhibits brittleness and a high susceptibility to autogenous shrinkage cracking, which can limit its practical use. [16]

As a response to these challenges, the authors of the article proposed an innovative approach to improve the Modulus of Elasticity in concrete without compromising its compressive strength and brittleness. The proposed method involves the addition of carbon nanotubes (CNTs) and carbon nanofibers (CNFs) in to the concrete mix. The unique properties of these nanomaterials such as their high aspect ratio and exceptional mechanical strength, can enhance the interfacial bond between the cement matrix and the aggregates, resulting in a stronger and more durable concrete.

Overall, while conventional methods for enhancing the Modulus of Elasticity in concrete have limitations the use of nanomaterials such as CNTs and CNFs offer a promising alternative that can lead to a stronger and more durable concrete. This new way of tackling the problem has the potential to revolutionize the construction industry and contribute to the development of more sustainable and resilient infrastructure. [16]

2.2.2 Reinforcement

The addition of reinforcement to concrete structures is an essential step in enhancing their lateral stability. Reinforcement can come in various forms, such as steel bars or Fiber-reinforced polymers and each type has a unique set of properties that can contribute to the overall stability of the structure. When used correctly, these materials can greatly improve the stiffness and strength of concrete structures, making them more resistant to cracking and failure under lateral loads.

Fiber-reinforced polymers, for instance, are particularly effective at improving the stiffness of concrete structures. These materials work by reducing the occurrence of cracks on the tension parts of the concrete section, thereby improving the overall structural stiffness of the concrete member. The incorporation of fibers enhances the mechanical characteristics of concrete such as tensile strength, flexural strength, and ductility performance. Increased tensile strength would result in the reduction of cracks and increase in the overall stiffness of the member. Tensile strength of reinforcement bar helps Localize the formation of cracks and ensures that the concrete member remains uncracked in certain most parts of the member. [17] This would make sure that the stiffness of the whole member the effects of tension stiffening.

It is worth noting that the type and size of reinforcement used, as well as its placement within the concrete structure, can have a significant impact on the lateral stability of the structure. Careful consideration must be given to the design and placement of reinforcement to ensure that the structure is able to withstand the lateral loads it will be subjected to. The effects of tension stiffening increases as the reinforcement ratio decreases. [18]

In conclusion, reinforcement plays a crucial role in improving the lateral stability of concrete structures. The use of materials such as steel bars and fiber-reinforced polymers can greatly enhance the stiffness and strength of concrete, reducing the likelihood of cracks and failure under lateral loads. Proper design and placement of reinforcement are critical to ensure that the structure is able to withstand the forces it encounters during its life time.

2.2.3 Geometry

The lateral stability of a concrete structure is greatly influenced by geometrical factors including the shape, size, and orientation of its structural members. The selection of a particular cross-sectional shape greatly impacts the stability of the structure, with circular and rectangular shapes being known to provide better lateral stability compared to other shapes. This is due to the fact that these shapes tend to have a better second moment of area when compared with other shapes having the same cross-sectional area.

Moreover, it is important to consider the aspect ratio of the building, which refers to the height-to-width ratio of the structure. A structure with low aspect ratio tends to be more susceptible to lateral loads and instability when compared to a structure with a higher aspect ratio. Therefore, when designing a concrete structure, it is essential to take into account these critical factors to ensure that the structure is stable and safe. Buildings with aspect ratio, less than 1:4, tend to be more susceptible to second order effects. In such cases the stability check is mandatory. [15] The shape of the cross-section and the orientation of structural members shall also be given due emphasis during the design process to improve the lateral stability of the structure.

2.2.4 Loading Conditions

The stability of a concrete structure is subject to multitude of variables, with the type and magnitude of lateral loads being some of the major parameters. Natural disasters like earthquakes and strong winds are powerful enough to generate significant lateral loads, resulting in structural instability. In addition to these forces, man-made loads such as those originating from construction equipment or traffic, can also impact the stability of a concrete structure.

The severity of the impact depends on the direction and duration of the lateral load with longer-duration loads having a more profound impact compared to shorter-duration loads. Stability of systems under quasistatic application of external forces is much different from stability analysis of systems subject to lateral loads that vary with time. [19] A large class of dynamic stability problems where the load varies sinusoidally with time have been studied by Bolotin. These types of dynamic loads are called a Bolotin parametric loads. Bolotin has shown that all systems that are subject to loss of stability under quasistatic loads are also subject to loss of stability under the dynamic Bolotin parametric loads. [20]

Therefore, engineers and designers must carefully consider the type, magnitude, direction, and duration of lateral loads when designing and constructing concrete structures to ensure their stability and safety.

2.2.5 Modelling and Analysis

It is absolutely essential to evaluate the lateral stability of concrete buildings in order to guarantee their safety and dependability. Exact models and examination techniques must be adopted in order to precisely evaluate the structure's behaviour while exposed to lateral forces. Over the years, a number of advanced techniques have been created to investigate the lateral stability of concrete buildings including finite element analysis and nonlinear dynamic analysis.

Recently, these methods have been widely used to study the response of concrete structures to lateral loads. These investigations have been very advantageous in giving us a better understanding of the stability and behaviour of concrete buildings, which in turn has led to the construction of safer and sound structures. It is essential to keep in mind though that the accuracy of these models and methods of analysis can be influenced by various factors, such as the complexity of the model and the analysis technique used. Models that are more detailed in presenting existing realities will generally yield a more precise representation of the structure and its response to lateral loads. Therefore, choosing the right level of detail in the model is of paramount importance to accurately predict the lateral stability of concrete buildings.

The resistance to seismic events of existing buildings that are designed to gravity loading only were studied. Vulnerability studies on the existing building stock require that a large number of buildings are analyzed to obtain statistically significant evaluations of the seismic performance. Therefore, analytical evaluation methods need to be based on simplified methodologies of analysis which can afford the treatment of a large building population with a reasonable computational effort.

The comparison is performed for RC buildings designed only to vertical loads, representative of the "as built" in Italy and in Mediterranean countries with a building stock very similar to the Italian one. In Non-Linear Dynamic Analysis, (NLDAs) the non-linear and degrading behaviour, typical of the structures under consideration when subjected to high seismic loads, is evaluated using models able to capture, with adequate accuracy, the non-linear behaviour of RC structural elements taking into account stiffness degradation, strength deterioration, and punching effect. Results show that for some specific types of buildings, the simplified analyses techniques are in good agreement with NLDAs. [21]

The selection of the analysis technique can also impact the results. For instance, while finite element analysis is a popular and widely used technique, it may not be suitable for all types of concrete structures. In such cases, nonlinear dynamic analysis or other advanced techniques may be more appropriate.

To sum up, it is critical to have a precise determination of the lateral stability of concrete structures for guaranteeing their safety and dependability. Making use of innovative methods, such as finite element analysis and nonlinear dynamic analysis, can give important insights on how these structures respond to lateral loads. However, it is vital to consider the complexity of the model and the selection of analysis approach to get precise outcomes. [21]

2.2.6 Design Codes and Standards

Design codes and standards serve a critical purpose in ensuring the safety and stability of concrete structures especially when subjected to lateral forces. These codes and standards are a set of guidelines that aid in the design, construction and evaluation of concrete structures. They take into account various factors such as material properties, reinforcement, geometry, loading conditions, and analysis techniques that are necessary to maintain the stability of the structure.

The codes and standards establish requirements for the minimum strength and ductility of the concrete and reinforcement and specify the acceptable levels of deflection and displacement under lateral loads. They also give the procedures for designing and evaluating structures under different types of lateral loads, like those caused by earthquakes and wind actions.

In addition to safety considerations, these design codes and standards also incorporate provisions for including seismic and wind-resistant features in the design of concrete structures. These features help to reduce the impact of natural disasters enhancing the durability of the structure and protecting the occupants.

Overall, it is clear that design codes and standards are essential in giving a better insight into the lateral stability of concrete structures. They provide engineers and architects with the necessary guidelines and best practices to design structures that are safe, durable, and able to withstand lateral forces from various sources.

When designing for seismic action, the impact of seismic effects and other related actions can be calculated using a linear-elastic approach. However, to predict the nonlinear response of the structure accurate behaviour factors have to be taken into account. [3] Resistance condition against stability failure is also covered under Eurocode 8 section 4.4.2.2(2). The value of the drift sensitivity coefficient determines the stability classification of the structure under consideration. [3] The determination of this parameter is clearly stipulated in the introduction part of this paper.

2.2.7 Summary of factors affecting lateral stability

To summarize, the lateral stability of concrete structures is of a big importance when it comes to ensuring their safety and reliability under different types of lateral loads. There are several factors that can influence the stability of these structures, such as the material properties of concrete, the type and amount of reinforcement, the structural geometry, and the applied loading conditions. Additionally, the accuracy of the analysis techniques used to assess the stability of concrete structures is also crucial.

This literature review has delved into the existing researches on the lateral stability of concrete structures and has provided a comprehensive overview of the key factors that contribute to their stability. Furthermore, the review has highlighted the importance of designing and constructing concrete structures in accordance with established codes and standards that incorporate provisions for lateral stability under wind and seismic loads.

Overall, the lateral stability of concrete structures is a complex issue that requires careful consideration of various design factors and load conditions. By understanding the critical factors that impact the stability of concrete structures engineers and designers can create more resilient and reliable structures that can withstand the forces of nature and provide long-term benefits to society.

2.3 Fuzzy logic and Building Problem Assessment

Fuzzy logic is a modelling technique, that provides a means to handle situations where the truth of a statement is not strictly limited to true or false. In contrast to traditional binary logic, which results in only two answers (True and False) for every situation, fuzzy logic allows for degrees of truth or membership within a given set. By introducing the notion of degree in the verification of a condition, thus enabling a condition to be in a state other than true or false, fuzzy logic provides a very valuable flexibility for reasoning, which makes it possible to take into account inaccuracies and uncertainties. [22] By incorporating fuzzy logic into the building problem assessment, the extent to which torsional rigidity and lateral stability parameters are outside of the desired values can be better understood.

Fuzzy logic utilizes a fuzzy inference system (FIS) to process input data and generate output based on human interpretable rules. These rules convey the knowledge and expertise of specialists, enabling the system to make informed decisions. Fuzzy inference systems provide a means of imitating human reasoning and decision-making processes, making them particularly suitable for solving problems with imprecise or incomplete information. The purpose of fuzzy rule bases is to formalise and implement a human being's method of reasoning. As such it can be classed in the field of artificial intelligence. [23] Identifying building problems and determining the necessary structural modifications is a challenging task that goes beyond the scope of pure mechanics, and it usually requires for specialized expertise. This highlights how well-suited fuzzy logic is for assessing building problems.

Unlike traditional modelling techniques that require deep understanding of the underlying mechanics of a system, fuzzy logic can handle complex systems even when the precise relationships and dependencies are not fully known. This flexibility is particularly valuable in the context of building problem assessment, where numerous interrelated factors contribute to the overall problem depth. Fuzzy logic allows for the modelling of experience-based knowledge, enhancing the accuracy and reliability of the assessment process. The computer side of artificial intelligence has been really interested in fuzzy logic as it allows to bind to the psychological side. [22]

To illustrate the effectiveness of fuzzy logic, consider the following example: "I am really thirsty, but I have had a lot of water." As human beings, we effortlessly interpret this statement based on our past experiences and knowledge of drinking routines. We inherently understand the degree of thirst and the required amount of water per day, allowing us to make appropriate decisions. However, a computer, relying solely on the literal interpretation of the statement, would struggle to reach a meaningful conclusion. Fuzzy logic provides the framework to encode our experiential knowledge into logical rules, enabling a computer program to navigate such vague and context-dependent situations. Capturing and representing the vagueness and imprecision of everyday language in terms that a computer can understand and work with is one of the objectives of fuzzy logic. [24]

2.4 Previous studies on related topics

Researches conducted on related topics are discussed in this section. Researches that have employed phyton programming for solving structural problems are reviewed in order to be able to grasp the basic knowledges required for the completion of this paper. Few are mentioned below.

Eyosias demonstrated how cross-discipline collaboration with architecture is possible and how all structural design activities can be connected with one another. [25] Building design integration is carried out on a sample building employing Revit, ETABS, and SAFE in addition to more conventional applications. For each of these software packages, plugins and applications have been created to enable interoperability and allow them to function as a unified platform. Modelling, analysis, design and clash detection were all facilitated.

This paper is a case study done on a single model. On the other hand, the proposed thesis work will be done in such a way that it can be applied for all building models. Furthermore, lateral stability and torsional irregularity check will be done for a model and if the model doesn’t comply with the code restrictions, the software will propose new structural elements in the model, recheck the parameters and provides a structural layout complying with code requirements.

Irregularities are responsible for the structural collapse of buildings under the action of dynamic loads. [26] According to the study by Solomon, plan asymmetric buildings are extremely vulnerable to earthquake-induced damage because of torsional impacts in addition to translational ones, as shown by past and contemporary earthquake events. The goals of this thesis are to examine the torsional behaviour of reinforced concrete buildings with plan asymmetries under earthquake load using parameters that indicate the consequences, and to suggest a workable way to lessen the effects. Findings of these research paper are used as an input for this paper.

Iqbal and Ali studied the need for automatic structural detailing of line elements in BIM tools. [27] The major objectives of this paper are to review the non-seismic and seismic detailing philosophies of reinforced concrete (RC) line elements as well as to explain the need for automatic structural detailing of line elements in BIM systems. The capabilities of BIM tools in the structural detailing of line elements were reviewed and discussed after doing a literature analysis. Some features that could automate the selection of rebar in RC line elements were found to be lacking in BIM software. Following the overview, a detailed analysis of the numerous characteristics of seismic and non-seismic detailing of RC line members is given.

The study and design of structures must be done using computer programs due to the variety of structural configurations. [28] According to the study done by Sarvade and Pore, there are numerous commercial programs for designing reinforced concrete structures but they are costly and only allow for a small number of users. This program can be used to teach and learn about the design of concrete structures. The benefit of using Python for interactive design is that a designer can construct a custom software. Programs written in Python can also be turned into executables files that can be used on any computer without the need for the source code. The paper presents a few Python programs that have been created to improve teaching and learning. Details taken from this served as a base for developing programs that can solve structural problems.

Chapter 3 PROGRAM DESIGN AND IMPLEMENTATION

3.1 Introduction

Torsional behaviour of asymmetric building is one of the most frequent sources of structural damage and failure during strong ground motions. [29] The design of building structures that meet the requirements of torsional rigidity and lateral stability is a critical aspect of structural engineering. Traditionally, this design process has been carried out manually, which is time-consuming and can lead to errors. With the advancement of computer technology and software, however, there has been a growing interest in automating the design process to improve efficiency and accuracy. Moreover, using computer program creates a platform to engineer a more cost-effective design as compared with the current practice.

This paper presents a program designed to automate the process of designing building structures for torsional rigidity and lateral stability. The program utilizes an API to communicate with the ETABS structural analysis software, obtaining the necessary analysis results to evaluate the building's torsional and lateral stability behaviour. Based on these results, the program checks whether the building design satisfies the requirements of relevant building codes.

The purpose of this chapter is to provide a detailed description of the design and implementation of the program. Discussing the overall structure of the program including the various modules and their functionality will be looked at first. Description of the design decisions that were made and the challenges that were encountered during the development process are also be covered. The algorithms and code recommended formulations used to process and analyze the data obtained from ETABS are also discussed.

Overall, this chapter aims to provide a comprehensive understanding of the program's design and implementation, setting the foundation for the subsequent chapters focused on verification, design examples, conclusions and recommendation. The development of this program, is intended for contributing to the growing field of automated structural design and promote efficient and accurate building design practices.

3.2 Program Flow Chart

According to Chaudhuri, Program flowcharts act like mirrors of computer programs in terms of flowcharting symbols. They contain the steps of solving a problem unit for a specific result. [30] Flow charts for the various individual tasks the program can perform are described using tree diagrams shown from Figure 3-1 to Figure 3-4. The figures show how the user and the structural analysis software interacts with each other. Internal processes that are happening while the program is running can also be seen from the diagram.

3.2.1 Flow chart for Stability Analysis

The flowchart shown in **Figure 3-1** shows the process flow of the Stability Analysis task the program is capable of performing. While calculating the drift sensitivity coefficient of the building model, the program extracts analysis results from ETABS through the API and calculates the drift sensitivity coefficient using code formulations and input from the user. The calculated value is then compared to code requirements and results are presented in a table format on the user interface.

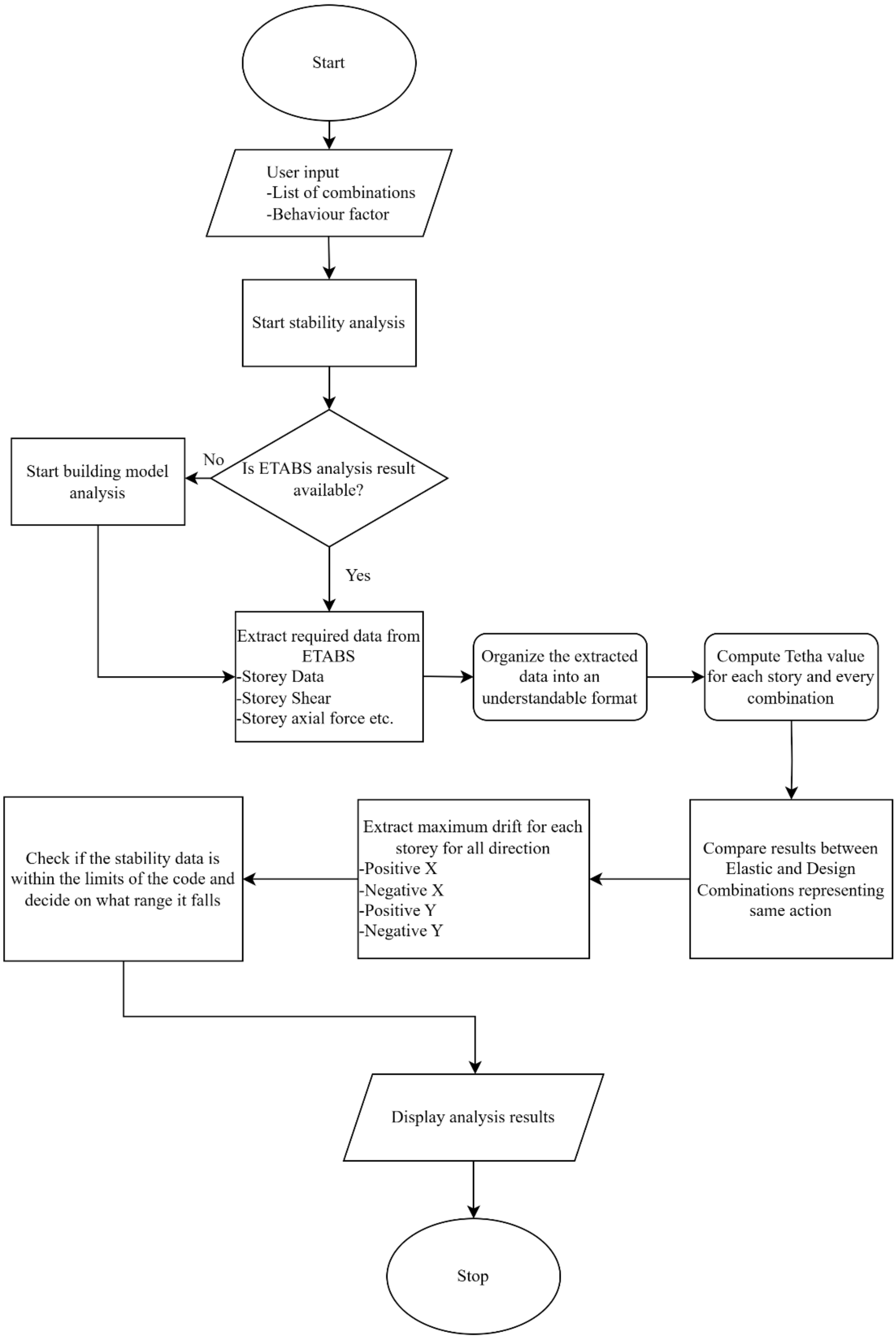


Figure 3-1 Flow chart for Stability Analysis

3.2.2 Flow chart for Torsional Rigidity Check

The flowchart shown in **Figure 3-2** shows the process flow of the Torsional Rigidity Check task the program is capable of performing. While calculating checking for torsional rigidity of the building model, the program extracts analysis results from ETABS through the API and calculates torsional radius and other required parameters using code formulations and input from the user. The calculated value is then compared to code requirements and results are presented in a table format on the user interface.

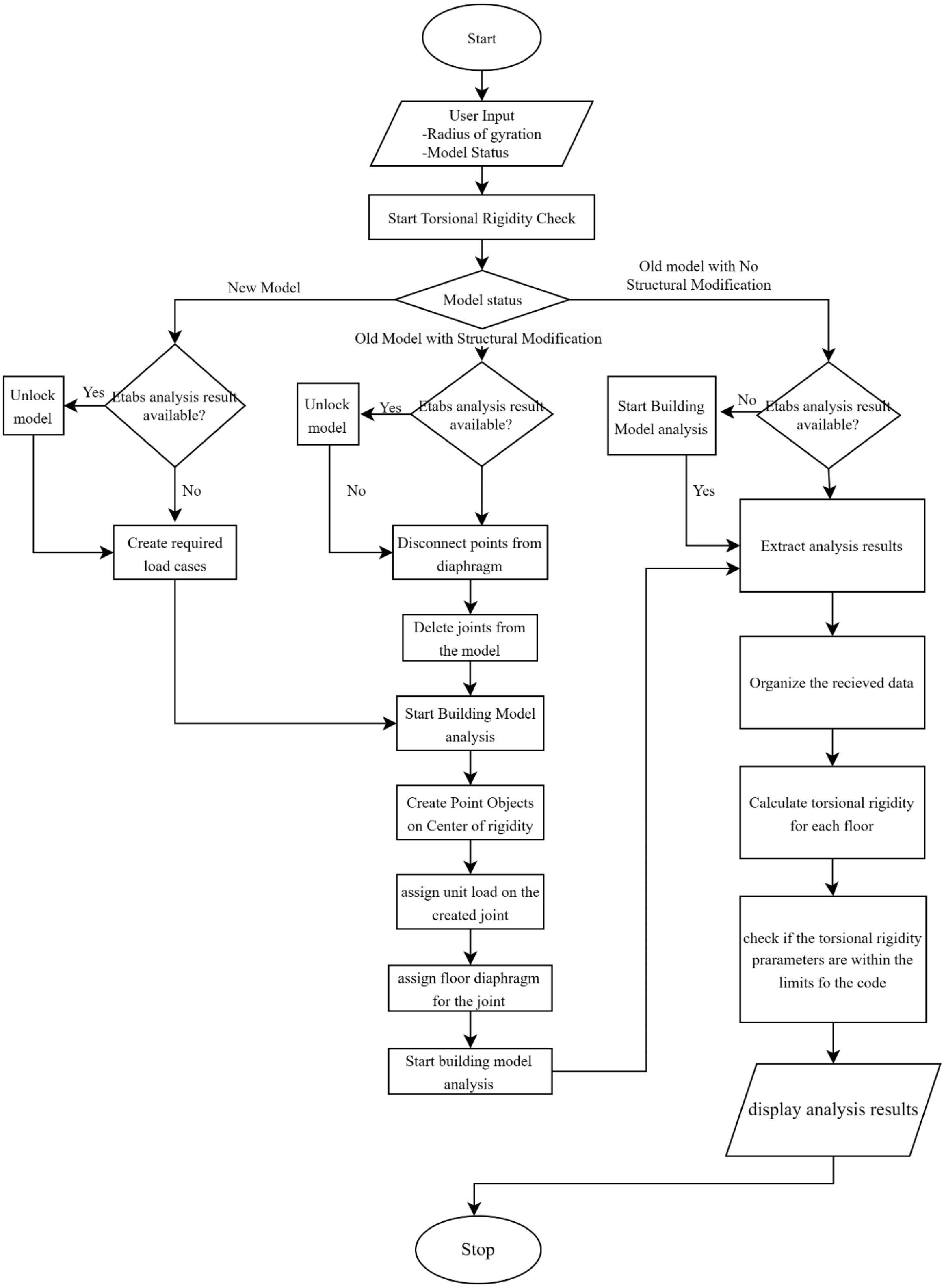


Figure 3-2 Flow chart for Torsional Rigidity Check

3.2.3 Flow chart for Stability and Torsional Rigidity Design

The flowchart shown in **Figure 3-3** shows the process flow of the Stability and Torsional Rigidity Design task the program is capable of performing. While designing for torsional rigidity and Stability of the building model, the program extracts analysis results from ETABS through the API and calculates all the required parameters using code formulations and input from the user. The calculated values are then compared to code requirements and if they don't meet the requirements of the code and the preference of the user, multiple solution measures are suggested for the user to choose from. Analysis results, detected problems and design solution are then presented in a table format on the user interface.

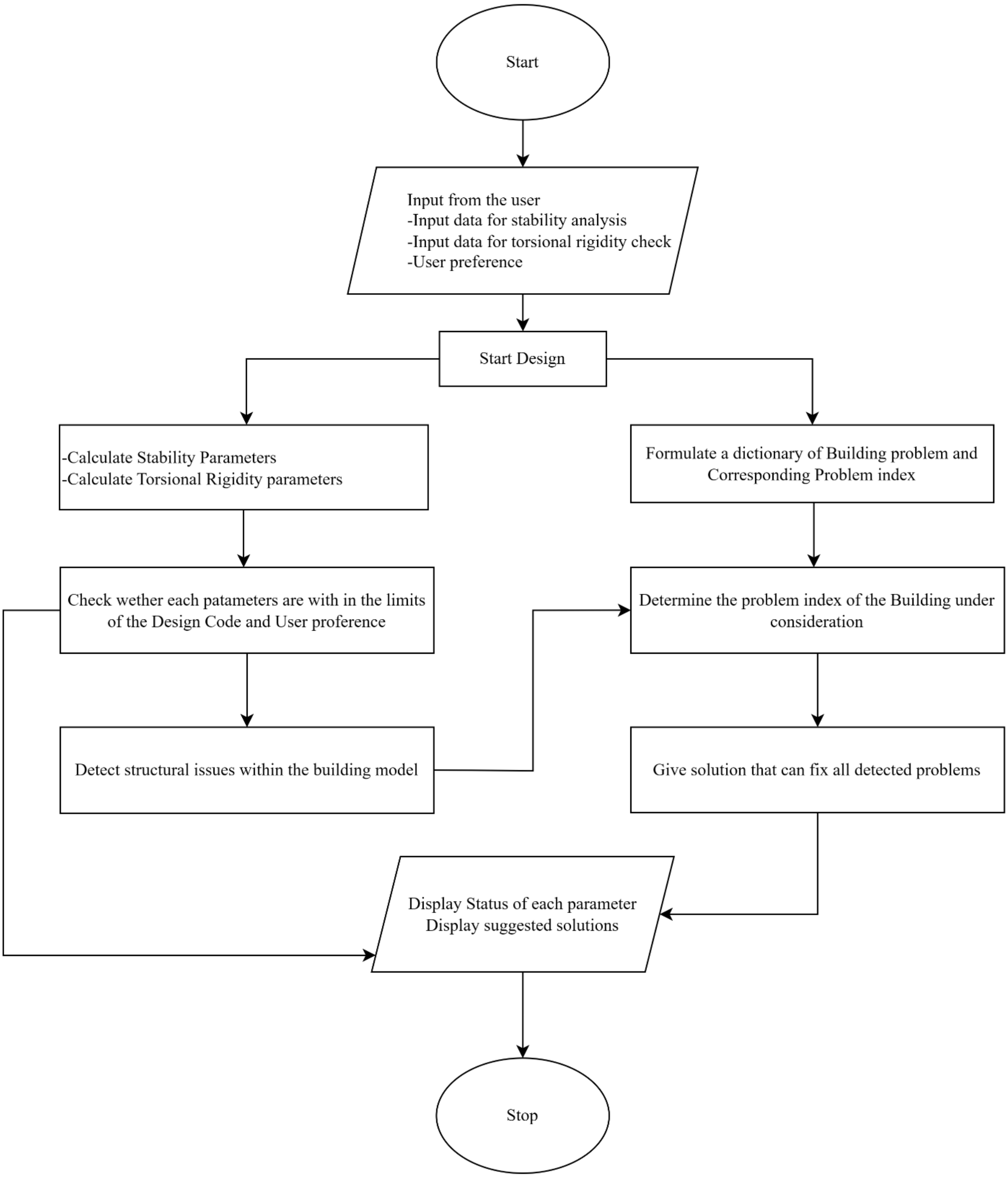


Figure 3-3 Flow chart for Stability and Torsional Rigidity Design

3.2.4 Flow chart for Model Automation

The flowchart shown in **Figure 3-4** shows the process flow of the Model Automation task the program is capable of performing. While making changes on the building model, the program extracts required parameters from ETABS through the API and input from the user to execute the required modelling request.

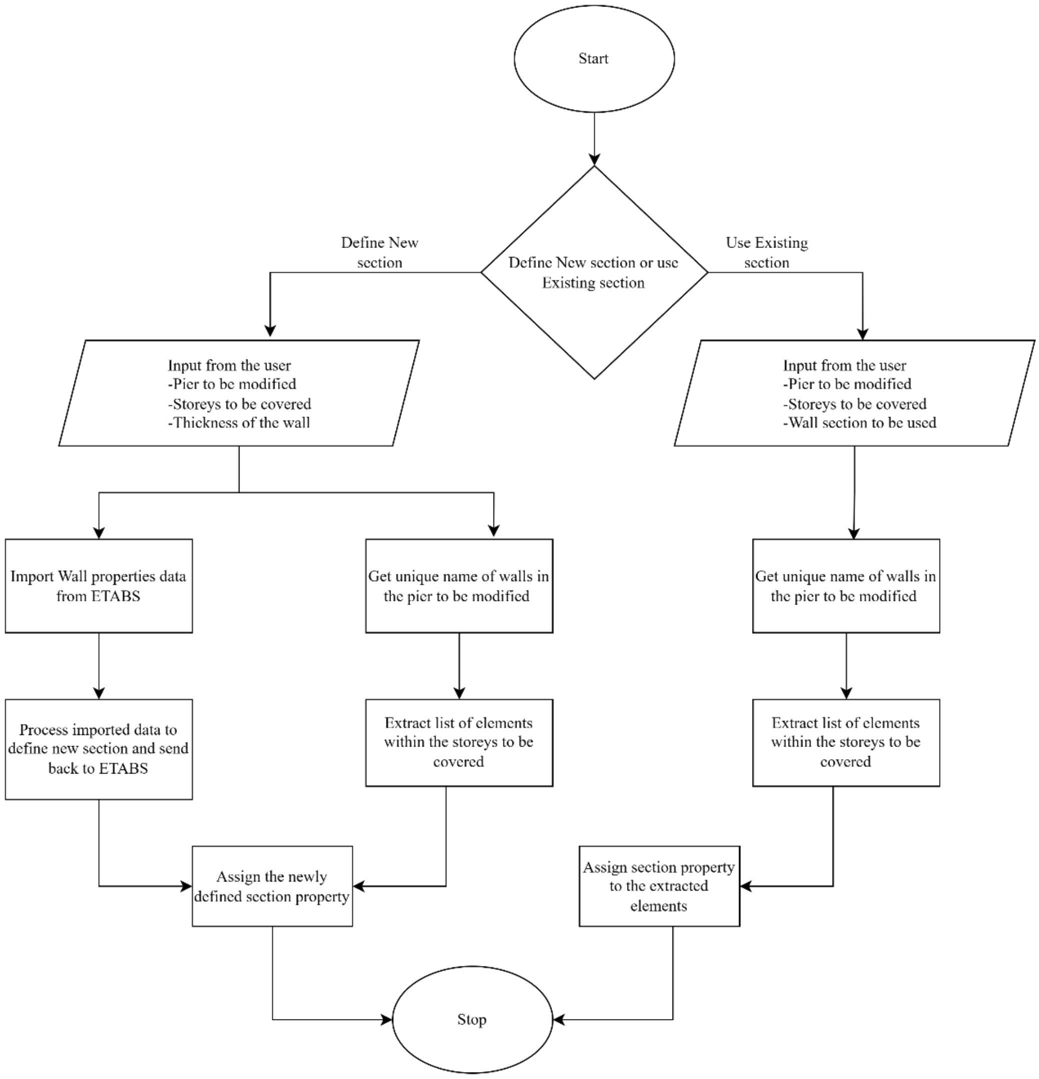


Figure 3-4 Flow chart for Model Automation

3.3 Program Structure Design

When it comes to the program's overall skeletal design, five different modules are prepared and then interconnected in a way that allows them to work together to achieve the program's overall goal of calculating stability and torsional rigidity parameters and designing the building model for stability and torsional rigidity.

Different tasks that are independent of one another can be performed by the program. For example, if the user only intends to get stability analysis results for a report, then they can easily get the required results without worrying about taking the time to calculate torsional rigidity data and integrated design for torsional rigidity and lateral stability. In order to make this a possibility, five different modules are prepared and interconnected through the concept of Object-oriented programming (OOP). The following subsections discuss each of the five modules in detail and how they are integrated through OOP.

3.3.1 Stability Analysis

The Stability Analysis Module is responsible for calculating the drift sensitivity coefficient of the building model. It extracts the analysis results obtained from the open instance of ETABS model, through the API interface. It also takes the user input from the program's user interface to calculate the drift sensitivity coefficient. The calculation of the drift sensitivity coefficient is essential for determining the building's overall stability during lateral loading. The module uses code recommended formulations and methods that takes into account the geometry and material properties of the building model, as well as the lateral loads applied to it, to calculate the drift sensitivity coefficient. The calculated value is then compared to the acceptable range of values stated by the code to determine if the building model satisfies the requirements of the design code. After calculating the drift sensitivity coefficient, the program detects on what range the values are categorized into. All the above calculated parameters are then organized in a table format to then be displayed to the user through the graphical user interface.

3.3.2 Torsional Rigidity Check

The Torsional Rigidity Check Module is responsible for checking whether the building model complies with the torsional rigidity requirements of the design code. It takes the analysis results obtained from the open instance of ETABS model, through the API interface. Values fed in by the user on the program's user interface to calculate the torsional rigidity parameters, such as the radius of gyration of the floor mass will also be taken as an input data. The module uses code recommended formulations and methods that takes into account the building's geometry, material properties, and applied loads to calculate the torsional rigidity parameters. The calculated values are then compared to the acceptable range of values provided by the user to determine if the building model satisfies the requirements of the design code. The above stated parameters and compliance criteria are then organized in a table format to then be displayed to the user through the graphical user interface.

3.3.3 Analysis and Design Integration

The Analysis and Design Integration Module is responsible for integrating the results obtained from the Stability Analysis Module and the Torsional Rigidity Check Module. It takes the calculated values from both modules and compares them ta a range of values provided by the user and the building code to determine if the building model falls within an acceptable range. If the results do not satisfy the requirements set by the user and the design code, the module suggests alternative solutions to the user, such as adding structural walls, changing the thickness of walls, or removing some structural walls. Analysis results for torsional rigidity check and lateral stability analysis are also made available to the user through the graphical user interface.

3.3.4 Model Automation

The Model Automation Module automates the process of adding or removing walls and changing the thickness of walls on the building model. It consists of a set of programming lines arranged in such a way that the user can perform operations like adding walls and removing walls automatically without the need for going to the ETABS model to which these modifications are to be applied. Each of the above listed operations have their own window with a set of entry boxes where the user can input information such as where to add walls, what thickness to use for the newly added walls and which walls to modify. The module is designed to make the process of modifying the building model more effortless and less time consuming.

3.3.5 Graphical User Interface

A GUI is a type of computer human interface on a computer. It solves the blank screen problem that confronted early computer users. [31] The Graphical User Interface (GUI) Module is responsible for providing a user-friendly interface for the program. It consists of a tab system developed using the Tkinter GUI development library, where clicking one tab lets the user choose from another set of tabs and so forth. The program's GUI has four main tabs, the Analysis, Design, Help and About tabs. The Analysis tab contains tabs that are only concerned with analysis and calculating the required parameters and do not continue into the design phase. The Design tab contains three sub-tabs; Input Data, Output Data, and Model Automation. The Input Data tab is where the user inputs the parameters necessary for stability analysis and torsional rigidity check. In addition to that, the user provides user preference data on the window of this tab. The Output Data tab displays the calculated results for stability analysis and torsional rigidity parameters. It also displays identified problem sets and suggested solutions. Finally, the Model Automation tab helps the user to implement the suggested solutions automatically by just putting in some required parameters.

3.3.6 Object Oriented Programming

Programs are organized as collections of cooperative, dynamic objects, each of which is an instance of some class. [32] Object oriented programming (OOP) is a programming technique that has become increasingly popular in recent years. OOP is based on the concept of objects. Each object has a set of attributes (data) and methods (functionality) that can be accessed by other parts of the program. OOP provides a modular approach to software development making it easier to write, maintain and modify code. Using OOP allowed for a more organized approach to software development, making it easier to integrate different modules of the program.

For instance, in the torsional rigidity module, all calculations were performed within the class called Determine Torsional Rigidity of Each Floor. Three methods were defined within the class. By encapsulating all the functionality related to torsional rigidity calculations within a single class, the codebase was organized and more easily maintainable.

OOP allowed for the integration of different modules within the software tool. For instance, when working on the graphical user interface module, the Determine Torsional Rigidity of Each Floor class within the torsional rigidity module is instantiated. Data is then extracted from the instantiated class by calling the Get Story Displacement and Rotation List method located within the instantiated class. This allowed for the integration of the graphical user interface module with the torsional rigidity module.

3.4 Implementation details and methods

This section provides an overview of the implementation process, including programming language selection, library utilization, API integration, coding practices, testing techniques, challenges encountered during the process, and their solutions.

3.4.1 Programming Language

Python was chosen as the programming language for the development of the program. One reason for this choice is that, vast number of libraries are available in Python. Additionally, Python is easy to learn, read, and write. Furthermore, Python's syntax is highly expressive, allowing programmers to write code with fewer lines.

3.4.2 Tkinter Library

Tkinter, a Python Graphical User Interface (GUI) producing library was used to create the graphical user interface for the program. One advantage of Tkinter is its ability to organize multiple windows using tabs. Which helps reduce the complexity of the graphical user interface. Tkinter is also highly customizable and have a large community that supports it.

3.4.3 ETABS API Integration

APIs as the collection of codes, packaged with interfaces that aid other developers to use it. [33] ETABS is a widely used structural analysis software and it is chosen as the analysis result provider for the program. ETABS API integration is Utilized to communicate with the structural analysis software. The primary reason for using ETABS API integration is to increase the number of users of the program by taking advantage of the popularity of ETABS in the country.

3.4.4 Coding Practices

The torsional rigidity analysis program was developed using simple programming techniques wherever possible. Every task performed by the program was commented to facilitate the understanding of the code for whoever is working on the code. Additionally, other good coding practices, such as modularization and the use of functions, were also used. These coding practices make the code easier to read, maintain, and modify.

3.4.5 Testing Techniques

Testing the torsional rigidity analysis program was carried out using hand analysis of a B+G+15 building model. Results from each programming step were printed out to track the program's progress and ensure that it was functioning correctly. This approach made coding relatively easier as any problems encountered were detected and resolved right from the beginning of the coding process.

3.4.6 Challenges Encountered

Typically, when checking a building for torsional regularity, it is necessary to analyze the building model twice. During the first analysis, the center of stiffness of the building floors is determined because the loads applied to obtain the required torsional rigidity parameters are applied at this point. Subsequently, the second analysis is conducted to obtain displacement and rotation data for each floor induced by these loads.

However, for building models that are large in size, conducting analysis twice can be time-consuming and impractical. To address this issue, the program offers three options that users can choose from, to decrease the number of times analysis needs to be conducted. For instance, the third option for the model status represents models that has been analyzed by the program for torsional rigidity and no structural modification is done after that. The center of rigidities of these types of models doesn't have to be recalculated. This means that, analyzing the structure for calculating its center of stiffness is not required, and the number of analysis required for the completion of the task is now reduced by one.

Other major challenges encountered during the development of the program includes addressing issues related to the graphical user interface tab organization and organizing the received analysis results data through the API interface.

CHAPTER 4 USER INTERFACE AND DATA REQUIREMENT

4.1 Introduction

The user interface is a crucial component of any software program, as it provides the means for users to interact with the system and perform tasks efficiently. In this chapter, we will discuss the user interface of the developed program which is designed to design buildings for stability and torsional rigidity. The user interface is built using T-kinter a powerful graphical user interface development python-library, that allows for the creation of a tab-based system. By using tabs users can easily navigate through the various functions of the program and choose the appropriate tab for the task at hand.

The user interface is divided into two four main tabs: Analysis tab, Design tab, Help and About tabs. The analysis tab is dedicated solely to the analysis and calculation of stability and torsional rigidity parameters. The analysis tab consists of only two tabs namely Stability analysis and torsional rigidity tabs. On each of these tabs the user feds in input data for the calculation of lateral stability and torsional rigidity. Windows of these tabs also consists of output results where by the user gets tabular data regarding the required parametric calculations.

On the other hand, the design tab includes additional functionality to identify problems, suggest solutions, and aid the user in implementing the suggested solutions automatically. The design tab consists of three sub-tabs: input data, output data, and model automation. The input data tab allows the user to enter the necessary parameters for stability analysis and torsional rigidity checks, as well as their preferences for acceptable values of lateral stability parameters. The output data tab displays the calculated results in a table format and compares them with code limitations to determine if the model meets the necessary requirements. It also suggests solutions to any problems that are detected. Finally, the model automation tab provides the means for the user to implement the suggested solutions automatically.

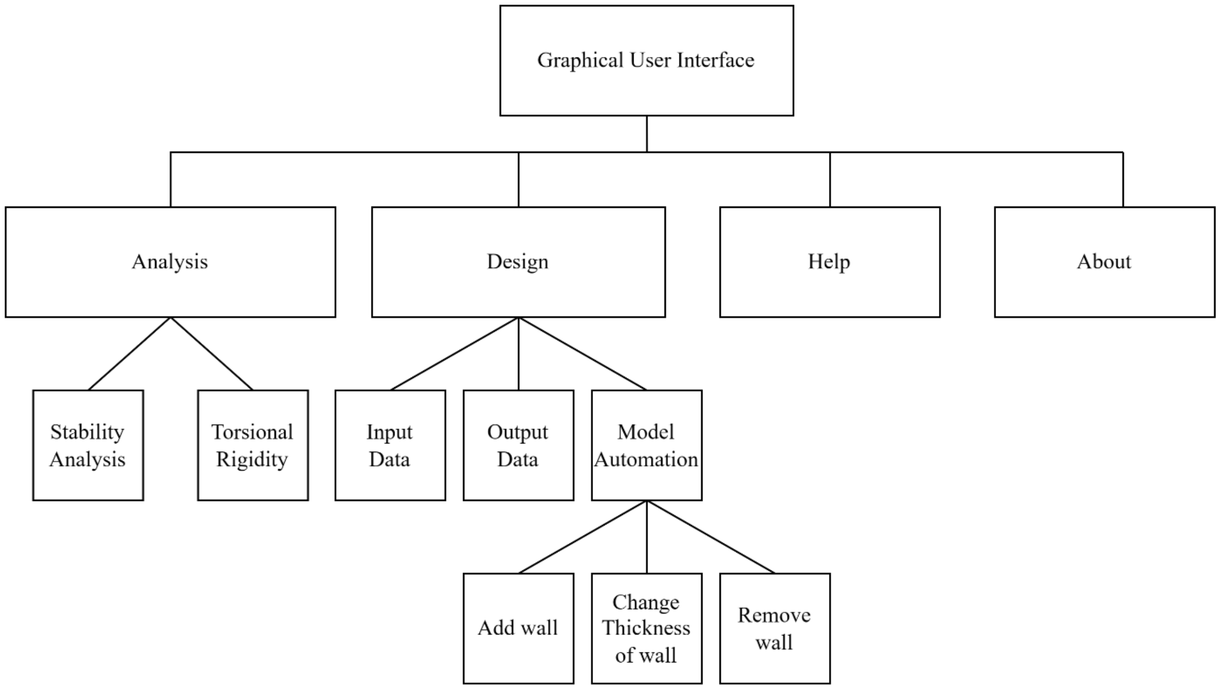


Figure 4-1 Tab System of the GUI

To ensure that the building is designed with appropriate lateral stability and torsional rigidity, the program requires various inputs from the user. These inputs are collected through data enquiry widgets displayed on different windows produced by the program. The program is designed in such a way that it can carry out specific tasks of analysis, design and automation. The individual tasks the program can carry out are listed as follows.

- Stability Analysis
- Torsional Rigidity Analysis
- Integrated Design for Lateral Stability and Torsional Rigidity
- Model Automation

The program is designed in such a way that it can carry out specific individual tasks at a time without operating on other tasks. For this reason, the user doesn't have to feed in data required for tasks that they don't intend to get output from. Data requirements that are supposed to be supplied by the user and output data that are provided by the program for each individual tasks are explained in the following subsections.

4.2 Stability Analysis

The Stability Analysis Window is one of the most important windows on the program. It allows the user to input various parameters that will be used by the program to perform stability analysis on the building model. **Figure 4-2** shows input data window prepared for Stability analysis.

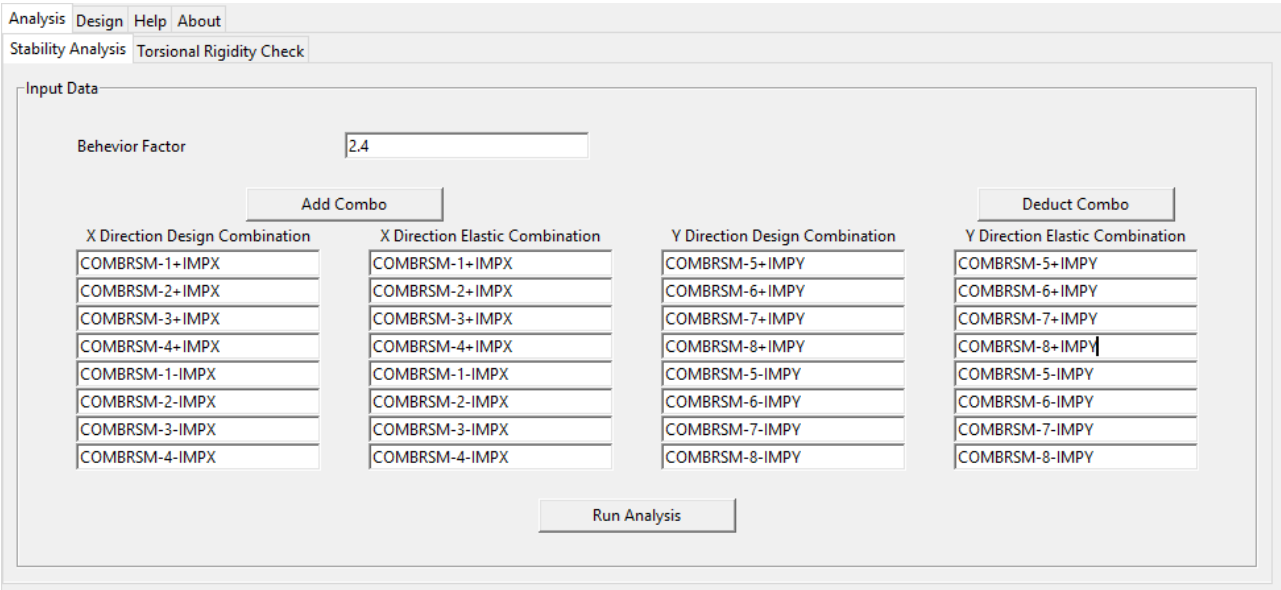


Figure 4-2 Stability Analysis input window

The behaviour factor of the building is one key parameter that need to be feed in by the user. The behaviour factor is a measure of the building's ability to dissipate lateral loads due to seismic actions. It represents the level of ductility and energy dissipation capacity of a structure during an earthquake event. The behaviour factor is usually derived from the type of lateral load resisting system of the building and the ductility class of the building.

Another important parameter that needs to be feed in by the user is the load combination for which the stability analysis needs to be performed on. Load combinations are used to represent the different possible combinations of forces that a building may experience during its lifetime. The program provides an "Add Combination" button that allows the user to add new load combinations. Similarly, the "Remove Combination" button allows the user to remove any combinations that are no longer required. This allows the user to carry out the analysis for any number of combinations that they intend to do the analysis for. The program finally chooses the combination that gives the most extreme result and deliver the result for that specific combination.

In addition to these parameters, the program collects additional required inputs from the analysis software. One of the data required for the calculation of lateral stability determination is analysis results from the structural analysis software. This data is transferred from ETABS to the stability analysis program through the API.

On the same window output data for stability analysis is provided to the user. the output data is summarized in table format. Four individual tables are made available to the user to get building information from. X-direction maximum, X-direction minimum, Y direction maximum and Y-direction minimum results are the four individual tables. Inside each table the combination that has resulted the maximum drift sensitivity coefficient for each floor is selected and the drift sensitivity coefficient for that combination is reported for each floor. Furthermore, on the status column of the table, data interpretation according to the code is made available to the user. Figures from Figure 4-3 to **Figure 4-6** show extracted data for a sample model in both X and Y axis, for positive and negative directions.

X Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
Roof	X	Max	COMBRSM-1+IMPX	0.026060501523764053	Good
6th	X	Max	COMBRSM-1+IMPX	0.043492588406281445	Good
5th	X	Max	COMBRSM-1+IMPX	0.0608963130797178	Good
4th	X	Max	COMBRSM-1+IMPX	0.07901020655661674	Good
3rd	X	Max	COMBRSM-1+IMPX	0.09255099997213431	Good
2nd	X	Max	COMBRSM-1+IMPX	0.09404240934980534	Good
1st	X	Max	COMBRSM-1+IMPX	0.08612493792644797	Good
Ground	X	Max	COMBRSM-1+IMPX	0.041138046160875116	Good

Figure 4-3 X-Direction Maximum stability data

X Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
Roof	X	Min	COMBRSM-1-IMPX	0.02605979114042456	Good
6th	X	Min	COMBRSM-1-IMPX	0.04349319824605174	Good
5th	X	Min	COMBRSM-1-IMPX	0.060896341156022556	Good
4th	X	Min	COMBRSM-1-IMPX	0.0790097992958874	Good
3rd	X	Min	COMBRSM-1-IMPX	0.09254998646440356	Good
2nd	X	Min	COMBRSM-1-IMPX	0.09404126578286166	Good
1st	X	Min	COMBRSM-1-IMPX	0.08612407185671658	Good
Ground	X	Min	COMBRSM-1-IMPX	0.04113736858014631	Good

Figure 4-4 X-Direction Minimum stability data

Y Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
Roof	Y	Max	COMBRSM-5+IMPY	0.022711079226486734	Good
6th	Y	Max	COMBRSM-5+IMPY	0.035129319183383946	Good
5th	Y	Max	COMBRSM-5+IMPY	0.047740733166877256	Good
4th	Y	Max	COMBRSM-5+IMPY	0.05869037501798841	Good
3rd	Y	Max	COMBRSM-5+IMPY	0.0638838653355249	Good
2nd	Y	Max	COMBRSM-5+IMPY	0.06038956955765659	Good
1st	Y	Max	COMBRSM-5+IMPY	0.04718671378335727	Good
Ground	Y	Max	COMBRSM-5+IMPY	0.02692904046263904	Good

Figure 4-5 Y-Direction Maximum stability data

Y Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
Roof	Y	Min	COMBRSM-5-IMPY	0.0335827699826098	Good
6th	Y	Min	COMBRSM-5-IMPY	0.049395870707040074	Good
5th	Y	Min	COMBRSM-5-IMPY	0.06387124873212664	Good
4th	Y	Min	COMBRSM-5-IMPY	0.07540837493340934	Good
3rd	Y	Min	COMBRSM-5-IMPY	0.07935911058746115	Good
2nd	Y	Min	COMBRSM-5-IMPY	0.07282946458777582	Good
1st	Y	Min	COMBRSM-5-IMPY	0.05468444791984356	Good
Ground	Y	Min	COMBRSM-5-IMPY	0.024410794700869973	Good

Figure 4-6 Y-Direction Minimum stability data

4.3 Torsional Rigidity Analysis

The Torsional Rigidity Analysis Window is another important window displayed while running the program. It allows the user to input various parameters that will be used by the program to perform Torsional rigidity check for the building model. **Figure 4-7** shows input data window prepared for Torsional rigidity check.

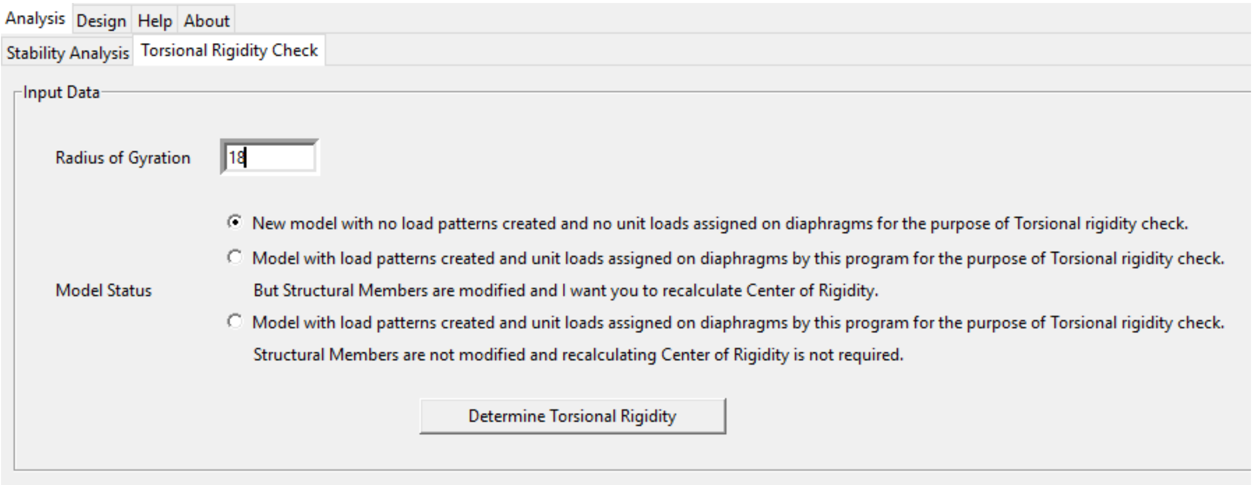


Figure 4-7 Stability Analysis input window

This window allows the user to input the radius of gyration of the building floor and status of the model for which analysis needs to be done. The radius of gyration is a measure of the distribution of mass in a building's floor system. It is a critical parameter for torsional stability as it affects the building's resistance to twisting due to lateral loads. The program requires the user to input the radius of gyration so that it can compare it against the calculated torsional radius, to determine torsional rigidity of the building under consideration.

The status of the model is another important parameter that needs to be input here. The status of the model describes whether the ETABS model under consideration has been analyzed by the program previously. This is important because the program makes modifications to the model during the analysis process like assignment of loads. If for example load application is done more than once, it can cause errors in the results by increasing the response of the structure for required load cases. The possible options for the model status parameter are made available for the user as a radio buttons. The available model status parameters are self-explanatory and are listed here under.

- New model with no load patterns created and no loads assigned on diaphragms for the purpose of Torsional rigidity check.

  If this option is selected, the program orders ETABS to run analysis and calculates center of rigidity of the building model. The program then applies actions on each floor of the building under newly defined load cases. Once again ETABS analysis is performed. The program then extracts results for the newly defined load cases, to calculate required parameters for torsional rigidity analysis.

- Model with load patterns created and loads assigned on diaphragms by this program for the purpose of Torsional rigidity check. But Structural Members are modified and Center of Rigidity of building floors shall be recalculated.

  If the user chooses this option, the program will remove any loads and load cases defined previously by itself and then orders ETABS to run analysis and calculates center of rigidity of the building model. The program then applies actions on each floor of the building and then once again order ETABS to perform analysis. It then extracts results for the newly added loads to calculate required parameters for torsional rigidity analysis.

- Model with load patterns created and loads assigned on diaphragms by this program for the purpose of Torsional rigidity check. Structural Members are not modified and recalculating Center of Rigidity is not required.

  If the user clicks on this option, then the program doesn't have to orders ETABS to run analysis and calculates center of rigidity of the building model. Because the task of calculating center of rigidity and assigning loads is already performed. The only thing left for the program to do is to extract results to calculate required parameters for torsional rigidity analysis. This means that the number of times

ETABS analysis is performed is reduced by at least one, saving the user from unnecessary waste of time.

Torsional rigidity check, in addition to these parameters, requires other information. The program collects these other required inputs from the analysis software. As is discussed in the explanation for the radio buttons, analysis results data is transferred from ETABS to the program through the API.

Analysis results for torsional rigidity check are provided to the user on this same window. The output data reported is summarized in table format. Two individual tables are made available to the user to get building information from. X-direction and Y-direction results are the two individual tables. Inside each table center of mass, center of rigidity, eccentricity or distance between the center of mass and center of rigidity and torsional radius are reported for each floor. Furthermore, comparisons between these parameters are done to check whether the floor under consideration is within the acceptable limits of the code. **Figure 4-8** and Figure 4-9 show extracted data for a sample model in both X and Y axis, for positive and negative directions.

X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	ls	Ecc_X<0.3rx	rx>ls
Ground	22.0128	22.0128	0.0	17.637793034256468	17.0	ok	ok
1st	22.0128	22.0128	0.0	17.828715599316787	17.0	ok	ok
2nd	22.0128	22.0128	0.0	17.396475056698705	17.0	ok	ok
3rd	22.0128	22.0128	0.0	16.99566277004031	17.0	ok	warning!
4th	22.0128	22.0128	0.0	16.640527793671964	17.0	ok	warning!
5th	22.0128	22.0128	0.0	16.33784092401358	17.0	ok	warning!
6th	22.0128	22.0128	0.0	16.11871158095912	17.0	ok	warning!
Roof	22.0128	22.0128	0.0	15.997042717870078	17.0	ok	warning!

Figure 4-8 X-Direction Torsional Rigidity data

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	ls	Ecc_Y<0.3ry	ry>ls
Ground	10.5597	10.161	0.39869999999999983	28.905730995836613	17.0	ok	ok
1st	10.6418	10.3286	0.31320000000000014	29.220289772388913	17.0	ok	ok
2nd	10.5951	10.3795	0.21560000000000024	26.102076460963737	17.0	ok	ok
3rd	10.5978	10.3804	0.2173999999999996	23.66858339137979	17.0	ok	ok
4th	10.6496	10.4199	0.22969999999999935	21.745544388962728	17.0	ok	ok
5th	10.6538	10.4862	0.1676000000000002	20.205653852088528	17.0	ok	ok

Figure 4-9 Y-Direction Torsional Rigidity data

4.4 Integrated Design of Lateral Stability and Torsional Rigidity

The Integrated Design of Lateral Stability and Torsional Rigidity Window is the most important and powerful window of the program. This window provides an entry widget where by the user feeds in all the input parameters required for lateral stability analysis and torsional rigidity analysis and design for both parameters. **Figure 4-10** shows input data window prepared for Torsional rigidity check.

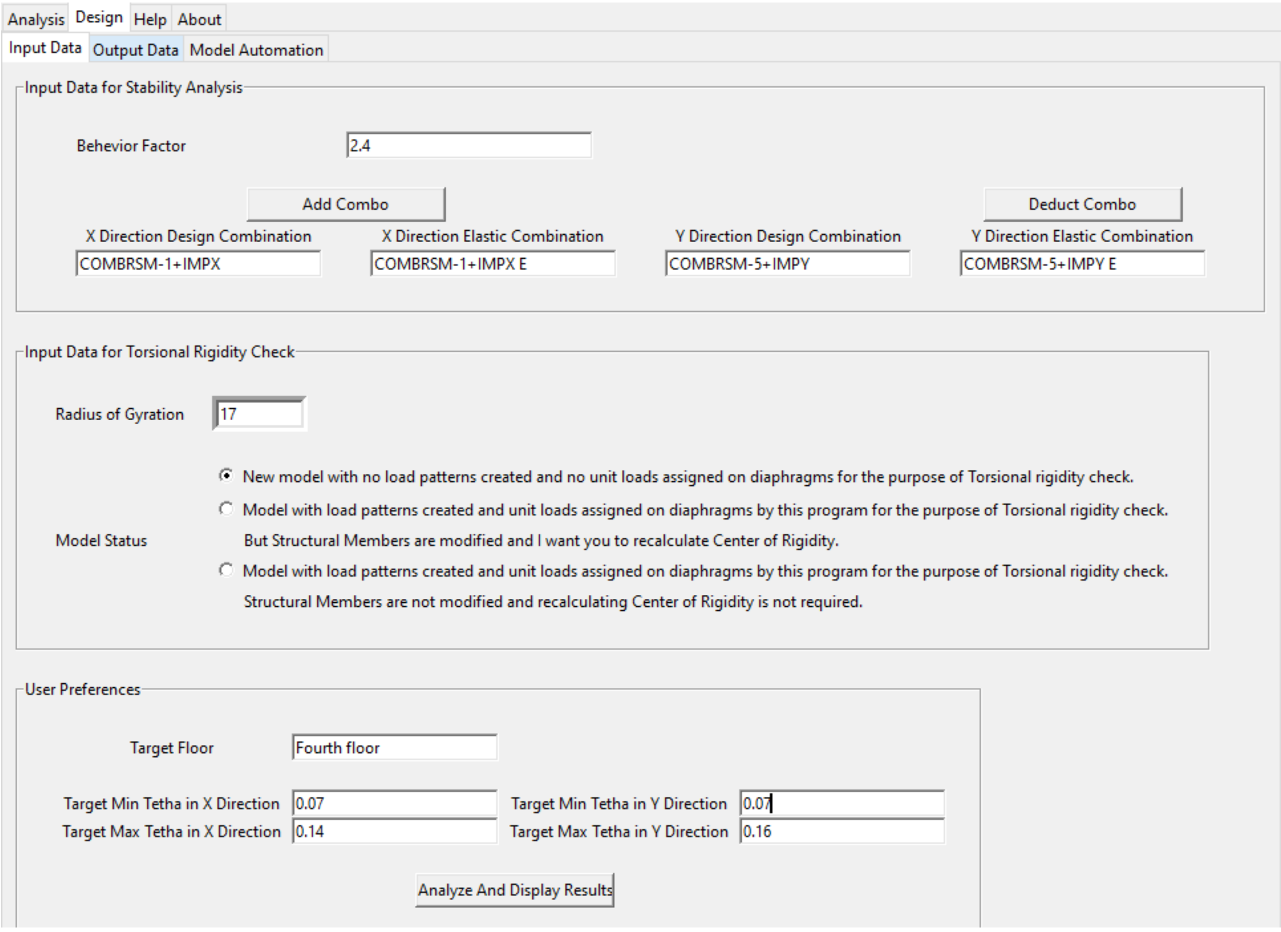


Figure 4-10 Integrated Design of Lateral Stability and Torsional Rigidity input window

The lateral stability and torsional rigidity parameters have been thoroughly discussed in their respective sections. Besides these parameters, the user can provide their design preferences, such as minimum and maximum drift sensitivity coefficient values. The program will optimize the design based on these inputs. It is essential to limit the drift sensitivity coefficient values for both directions as the program requires these parameters to suggest solutions efficiently.

Similar to the other tasks the program gathers necessary inputs from the analysis software to carry out the Integrated Design of Lateral Stability and Torsional Rigidity. one of the data required for this task is the analysis results obtained from the software. The API facilitates the transfer of this data from ETABS to the program.

Output Data tab on the other hand, provides the user with all the necessary analysis results and design suggestions. Stability data in both X and Y directions with maximum and minimum values for each direction is the first output of this task. The second output is the torsional rigidity data. Information like the torsional radius, mass center, center of rigidity and eccentricity data in both in both x and y directions are summarized in a table format and made available to the user. Whether these parameters are within the acceptable range set by the code is also incorporated in the table. To avoid repetition of data, the tables are not presented here and if the reader is interested in what the tables look like, Figure 4-6 and Figure 4-9 can be referred.

The output data that is different from the output results given by the analysis option of this program is the problem identification and suggested solution part of the result. On this part all the six parametric checks imposed by the code are compared against the standards and are classified as problematic and non-problematic. If any one, two or more of the parameters are found to be problematic, the program suggests alternative solutions to tackle the problem. The problem identification and Suggested Solutions part of the output is shown on **Figure 4-11**.

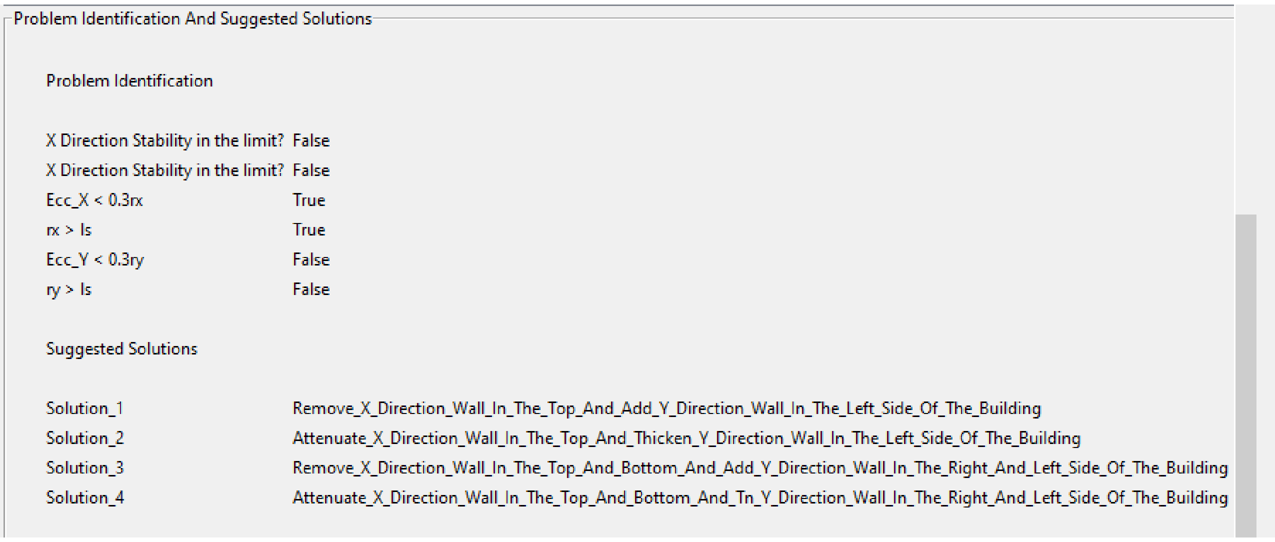


Figure 4-11 Problem Identification and Suggested Solutions

4.5 Model Automation

In the Model Automation window, there are several subsections that the user must choose from to make the desired modifications to the building model. The user will have to choose from adding walls, removing walls and modifying the thickness of the walls before getting the input window required for making structural alterations. The type of modification selected by the user will dictate the window that the user faces and therefor the subsequent input parameters to be fed into the program. Modification options available for the user are discussed in detail on the following sub sections.

4.5.1 Add Walls

If the user clicks on Add Wall tab under the Model Automation tab, a window that provides an entry widget where by the user feeds in all the input parameters required for adding new wall in to the building model. **Figure 4-12** shows input data window prepared for Adding structural walls in to the model.

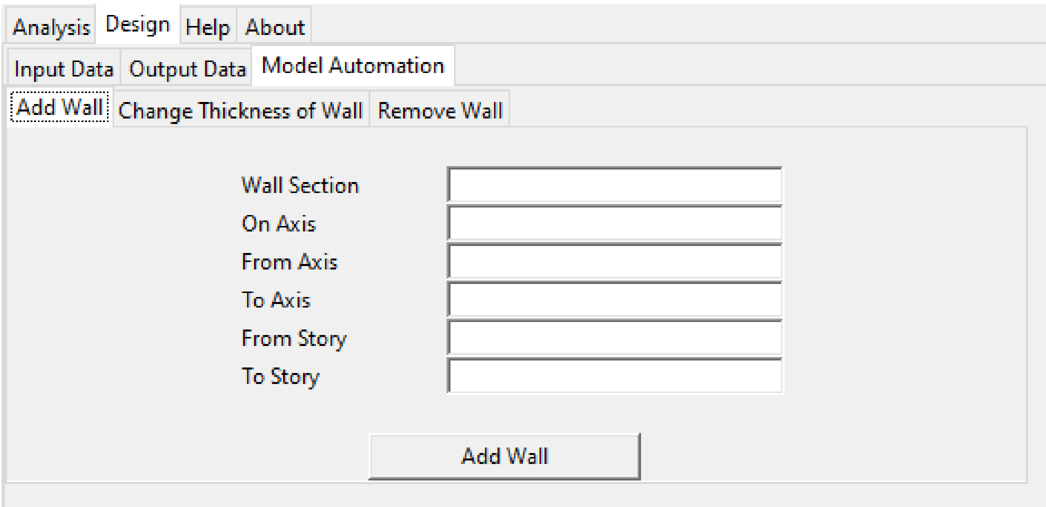


Figure 4-12 Input window for Adding Wall into the building model

If the user wants to add walls, they will be prompted to specify where the walls should be added in the building model. The location of the wall to be added is described using the grid system of the building model. On what axis the wall is to be aligned and from which orthogonally placed axis to which orthogonally placed axis the wall is to be drawn will also be fed in by the user. The direction of the wall to be added will also be fed in by the user. The input data for the direction of the wall to be added is always either one of X and Y. The user will decide between X and Y options basing up on what the minor axis of the proposed wall is.

The program also provides an entry box that allows the user to specify the desired story level from which the wall should start from. Similarly, the ‘To story’ level entry box allows the user to specify the desired story level up on which the wall should be terminated. Additionally, the user must specify the thickness of the wall to be added.

4.5.2 Remove Walls

If the user clicks on Remove Wall tab under the Model Automation tab, a window that provides an entry widget where by the user feeds in all the input parameters required for removing an existing wall from the building model. **Figure 4-13** shows input data window prepared for Removing structural walls from the model.

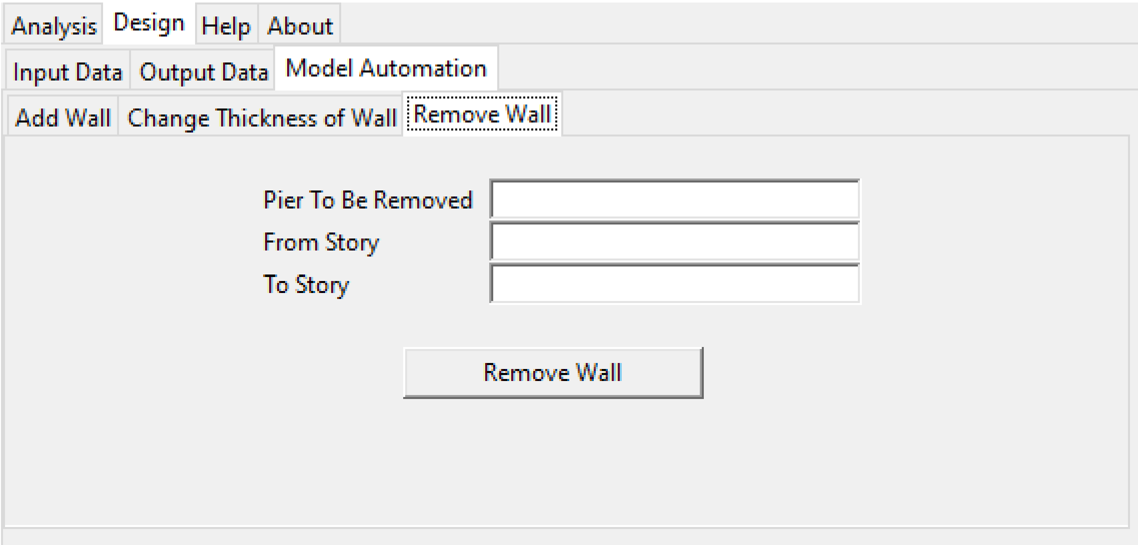


Figure 4-13 Input window for Removing Wall from the building model

If the user intended to remove walls from the structure, they must specify the pier to be removed. Again, the program provides an entry box that allows the user to select the pier to be removed. Removal of walls can sometimes be risky, as it may result in the loss of lateral stability. However, the program suggests to remove walls only after checking the analysis results for both torsional rigidity and lateral stability and removal of walls is the best option to force a way out of the detected problems.

Once again, the program provides an entry box that allows the user to specify the desired story level from which the removal of the walls should start from. Similarly, the ‘To story’ level entry box allows the user to specify the desired story level up on which the removal of walls should be terminated.

4.5.3 Change Thickness of Wall

If the user chooses to click on Change Thickness of Wall tab under the Model Automation tab, a window that provides two buttons by the name Define New Section and Use Existing Section will be displayed. An entry widget where by the user feeds in all the input parameters required for changing the thickness of a wall will then be displayed after one of the buttons is clicked.

Up on clicking the Define New Section button, a window with an entry box for the required data for defining new wall section, the pier to be modified and story data on which the pier shall be altered will be displayed. If on the other hand Use existing section button is clicked, another window with entry boxes for the existing wall section to be used, on what stories the modification shall be made and to what pier label the modification should be done will be displayed.

4.5.3.1 Define a New Section

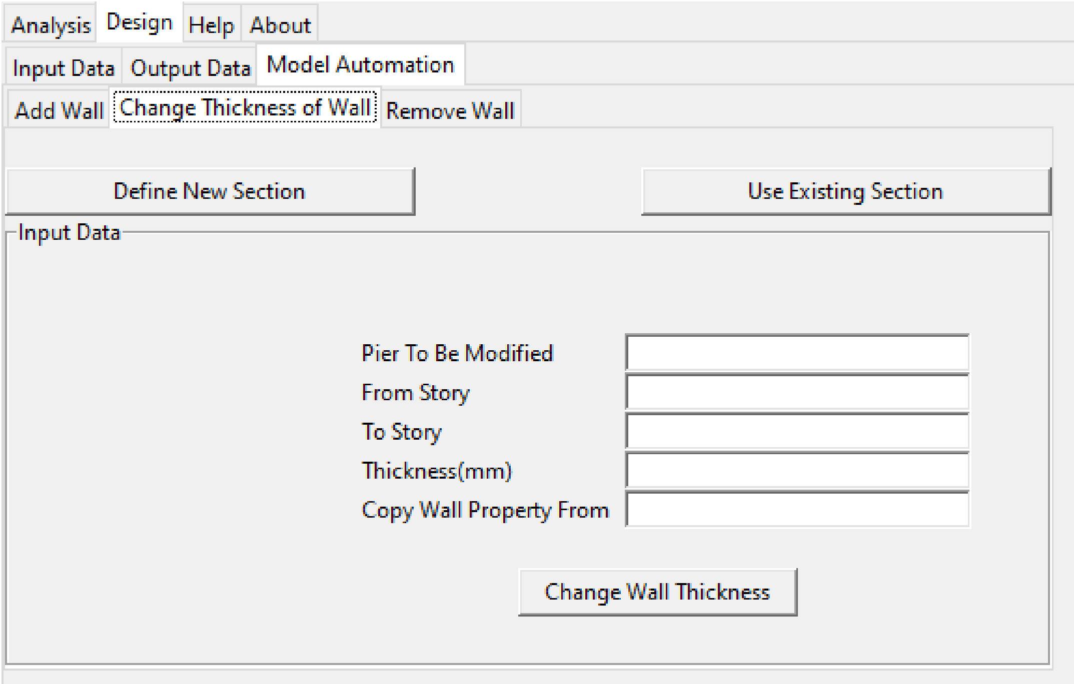


Figure 4-14 Input Window for Defining a New Section to Change Thickness of Wall

As can be seen from **Figure 4-14**, the window that is displayed when clicking the Define New section have entry boxes for necessary information like Pier To Be Modified, From Story, To Story, Thickness (mm) and Copy Wall Property From. The user inputs the name of the pier section they intend to change the thickness of on the Pier To Be Modified entry box. Once again, the user will get a chance to modify only some part of the pier section by feeding in the story after which the wall thickness should be changed and the story upon which the change in section property should be terminated, by feeding in story names in to the From Story and To Story entry boxes respectively.

On the Thickness (mm) entry box, the user is supposed to fed in the thickness of the wall section that want to define. All other section properties like stiffness modifiers for moment, shear axial force and so forth are to be extracted from an existing wall section available on the model. The name of the wall section from which wall property data is to be copied from will be fed in by the user on the Copy Wall Property From entry box.

4.5.3.2 Use an Existing Section

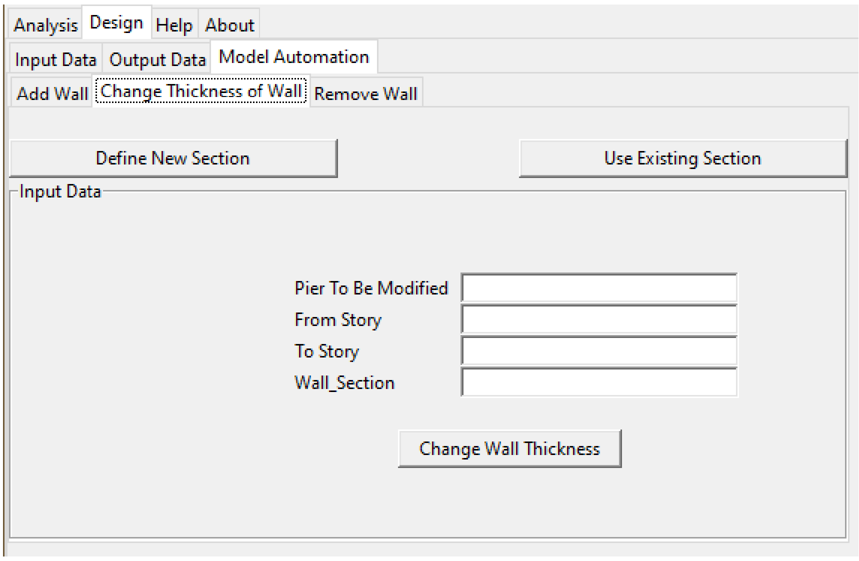


Figure 4-15 Input Window for Using an Existing Section to Change Thickness of Wall

As can be seen from **Figure 4-15**, the window that is displayed when clicking the Use an Existing Section have entry boxes for necessary information like Pier to Be Modified, From Story, To Story and Wall Section. The user inputs the name of the pier section they intend to change the thickness of on the Pier to Be Modified entry box. Once more, the user will get a chance to modify only some part of the pier section by feeding in the story after which the wall thickness should be changed and the story upon which the change in section property should be terminated, by feeding in story names in to the From Story and To Story entry boxes respectively.

Finally, on the last input expected from the user, the name of the wall section that is to be assigned for the selected pier will be fed in on the Wall Section entry box.

In conclusion, the Model Automation window is an essential feature of the program, allowing engineers to automate the process of modifying building models quickly. The input parameters required for each modification type ensure that the changes made to the model are precise and effective in meeting the lateral stability and torsional rigidity requirements.

CHAPTER 5 VERIFICATION AND DESIGN EXAMPLE

This chapter presents an example design and verification of the developed program. The main objective of this chapter is to validate the functionality of the developed program for designing buildings with torsional rigidity and lateral stability. This chapter also aims at providing a guidance on how to use the program. Both objectives are achieved by performing a manual analysis and comparing the results to those obtained from the developed program. Comparison against results of a standard documents is also presented in this chapter.

The first section of this chapter discusses the analysis and design of a real building model that is to be constructed. A manual analysis is performed to the building model for torsional rigidity and lateral stability. The same building model is then analyzed and designed by the developed program, and the results are compared to verify that the program functions as intended and can be applied to real-life design problems.

The second section of this chapter focuses on validating the developed program against a trusted document for this purpose a book by the title Eurocode 8: Seismic Design of Buildings: Worked examples is used as an example manual. The manual describes a building model using images, writings and numbers. The developers of the manual have performed a torsional rigidity analysis for the model. The building model is recreated, and the developed program is used to perform a torsional rigidity check. The results obtained are then compared to those presented in the manual to validate the accuracy of the developed program.

5.1 Analysis and Design Example

In this subsection, a real building model is analyzed designed for torsional rigidity and lateral stability. The building is first analyzed manually. The analysis is then replicated using the developed program to check the accuracy and reliability of the program. Then the model is designed for lateral stability and torsional rigidity. The design is performed using the developed program, to have a say on how efficient the program is for solving real-life problems.

5.1.1 Analysis

In the analysis subsection, manually calculated results for torsional rigidity and lateral stability are presented. The manual analysis is conducted according to the provisions of the code and the relevant calculation procedures are presented here. All relevant loads and load combinations are considered in the manual analysis, and the results are tabulated for easy comparison with the results obtained from the program.

The same building model is then analyzed using the developed program to verify its accuracy and reliability. The inputs required by the program, such as the behaviour factor are fed in to the program to match the conditions used in the manual analysis.

5.1.1.1 Modelling

The building model used for the design example section of this chapter is created following the requirements of the EURO CODE to ensure that it resembles the current structural design practice in the country. The building is a B+G+13+TERRACE building, and all its structural details, including staircases and ramps, are included in the model to ensure that it represents a real-life problem.

ETABS structural analysis and design software is utilized to create a three-dimensional representation of the building. Pictures of the architectural drawings of the model and a 3D view of the building model are presented in this subsection to give the reader a visual representation of the building model.

Figure 5-1 3D Architectural Representation

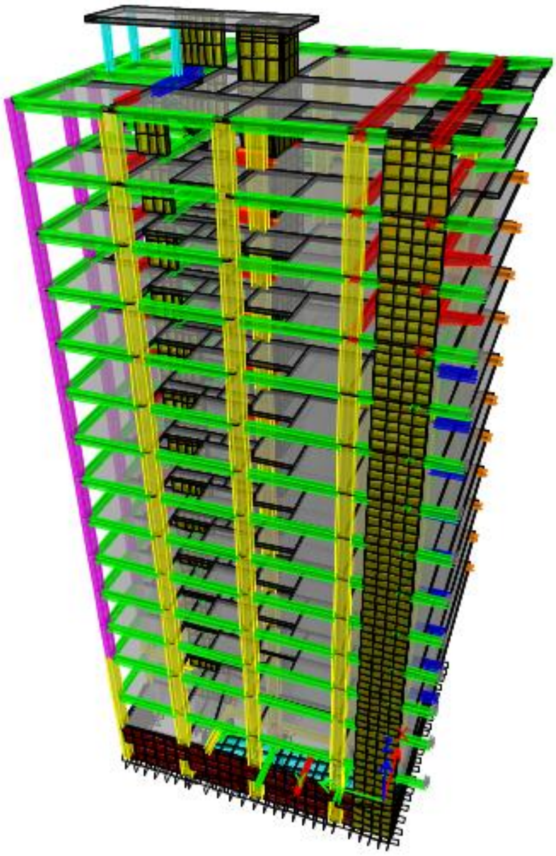


Figure 5-2 3D Structural Representation

5.1.1.2 Stability analysis

The manual analysis and the analysis using the developed program are both performed to check the stability of the building under consideration. The stability of the building is checked against seismic forces. The results of the manual analysis and the analysis using the developed program are then compared to ensure that the program accurately and reliably predicts the lateral stability of the building.

Two important things must be considered when performing displacement analysis. According to ES-EN1998-1 section 4.3.4(1) if linear analysis is performed (which is the case for this building), the displacements induced by the design seismic action shall be calculated on the bases of the elastic deformation of the structural systems. [3] And hence:

$$d_s = q_d \times d_e \tag{5-1}$$

where:

d_s is the displacement of a point of the structural system induced by the design seismic action

q_d is the displacement behaviour factor

d_e is the displacement of the same point of the structural system, as determined by a linear analysis based on the design response spectrum.

The second thing that needs to be considered according to the same clause is, the value of d_s doesn't need to be larger than the value derived from the elastic spectrum d_e.

To account for this clause, two response spectrum functions needed to be defined in ETABS. An Elastic spectrum (with behaviour factor =1) and a Design spectrum (with behaviour factor for the building type).

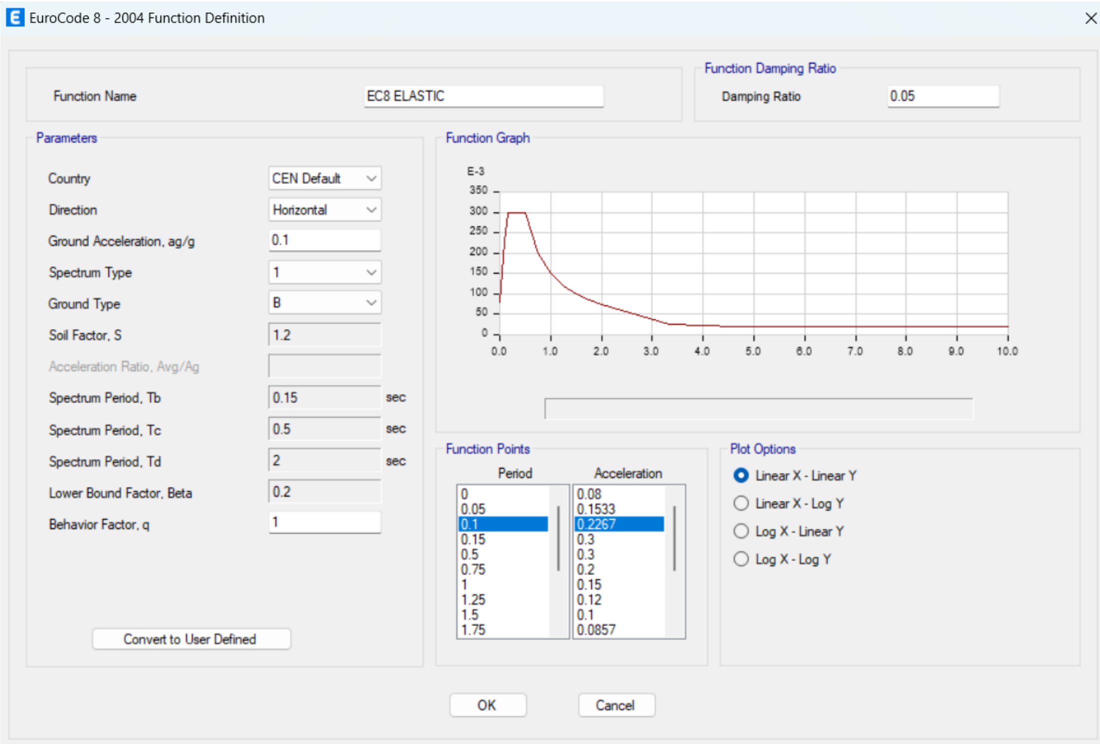


Figure 5-3 Elastic RSM spectrum

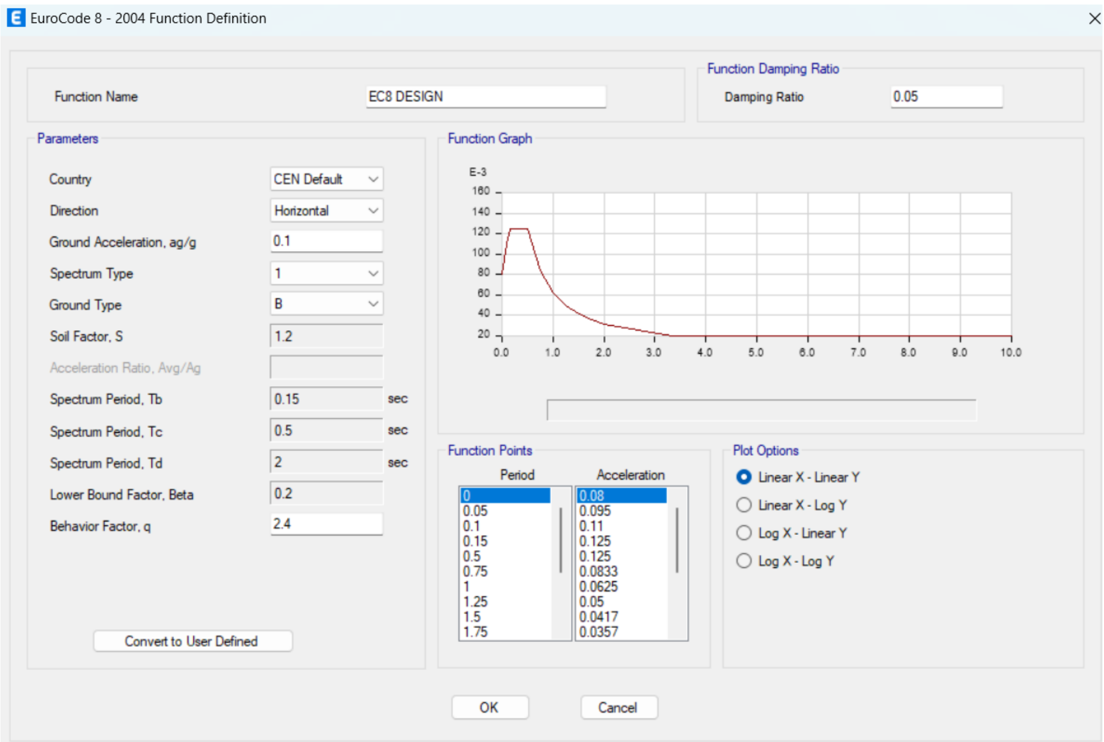


Figure 5-4 Design RSM spectrum

5.1.1.2.1 Manual calculation

Inter story drift sensitivity coefficient is calculated for all stories of the building for each seismic related design combinations. All the parameters required for the calculation are obtained from analysis results in ETABS. Values for P_{tot} and V_{tot} for each story and combination are obtained by exporting the story forces result in ETABS. Using the same approach, the inter story drift ratio defining the ratio between relative story lateral displacement and story height is obtained by exporting the Story drift results from ETABS.

Analysis is done for both the global X and global Y directions of the model. Furthermore, each global direction has two components called RSM max and RSM min. The max and min terms only show the direction of the extracted parameter. For this reason, four different cases are treated separately and are discussed as follows.

5.1.1.2.1.1 X-direction Maximum

Total axial force P_{tot}, total story shear V_{tot} and inter story drift ratio results are extracted from ETABS analysis software. Results for all seismic related combinations in the X direction and maximum step type are extracted for the purpose of drift sensitivity coefficient determination. Sample extracted data is shown in **Table 5-1** and **Table 5-2**.

Table 5-1 X-Max drift results

Story	Output Case	Case Type	Step Type	Direction	Drift
RT	COMBRSM-1+IMPX	Combination	Max	X	0.0016
RT	COMBRSM-2+IMPX	Combination	Max	X	0.0016
RT	COMBRSM-3+IMPX	Combination	Max	X	0.0016
RT	COMBRSM-4+IMPX	Combination	Max	X	0.0016
RT	COMBRSM-1-IMPX	Combination	Max	X	0.0012
RT	COMBRSM-2-IMPX	Combination	Max	X	0.0012
RT	COMBRSM-3-IMPX	Combination	Max	X	0.0012
RT	COMBRSM-4-IMPX	Combination	Max	X	0.0012
RT	COMBRSM-1+IMPX E	Combination	Max	X	0.0017
RT	COMBRSM-1-IMPX E	Combination	Max	X	0.0013
RT	COMBRSM-2+IMPX E	Combination	Max	X	0.0017
RT	COMBRSM-2-IMPX E	Combination	Max	X	0.0013
RT	COMBRSM-3+IMPX E	Combination	Max	X	0.0017
RT	COMBRSM-3-IMPX E	Combination	Max	X	0.0013
RT	COMBRSM-4+IMPX E	Combination	Max	X	0.0017
RT	COMBRSM-4-IMPX E	Combination	Max	X	0.0013

Table 5-2 X-Max story forces

Story	Output Case	Case Type	Step Type	Location	P	VX
					kN	kN
RT	COMBRSM-1+IMPX	Combination	Max	Top	598.7188	99.5452
RT	COMBRSM-1+IMPX	Combination	Max	Bottom	896.2438	99.5452
RT	COMBRSM-2+IMPX	Combination	Max	Top	598.7188	99.5452
RT	COMBRSM-2+IMPX	Combination	Max	Bottom	896.2438	99.5452
RT	COMBRSM-3+IMPX	Combination	Max	Top	598.7188	99.5452
RT	COMBRSM-3+IMPX	Combination	Max	Bottom	896.2438	99.5452
RT	COMBRSM-4+IMPX	Combination	Max	Top	598.7188	99.5452
RT	COMBRSM-4+IMPX	Combination	Max	Bottom	896.2438	99.5452
RT	COMBRSM-1-IMPX	Combination	Max	Top	598.7188	107.0856
RT	COMBRSM-1-IMPX	Combination	Max	Bottom	896.2438	107.0856
RT	COMBRSM-2-IMPX	Combination	Max	Top	598.7188	107.0856
RT	COMBRSM-2-IMPX	Combination	Max	Bottom	896.2438	107.0856
RT	COMBRSM-3-IMPX	Combination	Max	Top	598.7188	107.0856
RT	COMBRSM-3-IMPX	Combination	Max	Bottom	896.2438	107.0856
RT	COMBRSM-4-IMPX	Combination	Max	Top	598.7188	107.0856
RT	COMBRSM-4-IMPX	Combination	Max	Bottom	896.2438	107.0856

Now that the analysis results required for the determination of drift sensitivity coefficient are extracted, θ values for each storey and each combination can be calculated.

Inter storey drift calculation for the 13th floor, combination COMBRSM-4-IMPX and RSM-min is shown below.

P_{tot} = 13552KN
V_{tot} = 932KN
d_r/h = 0.00187
$d_{r,e}/h$ = 0.0021

$$\theta = \frac{p_{\text{tot}} \times d_{\text{r}}}{V_{\text{tot}} \times h}$$

$d_s = q_d \times d_e = 0.00187 \times 2.4 = 0.0045$, which is larger than the elastic drift value so the elastic one is taken.

$$\theta = \frac{13522KN}{932KN} \times 0.0021 = 0.03046$$

Sample inter storey drift calculation for all stories and all combinations in the X-Max direction of the sample building is presented on **Table 5-3**.

Table 5-3 θX (Max) for all combinations

Story	Output Case	Step Type	Location	P	VX	dsX * q	deX	θX (Max)
				kN	kN			
RT	COMBRSM-1+IMPX	Max	Top	598.719	99.545	0.004	0.002	0.010
RT	COMBRSM-2+IMPX	Max	Top	598.719	99.545	0.004	0.001	0.008
RT	COMBRSM-3+IMPX	Max	Top	598.719	99.545	0.004	0.002	0.010
RT	COMBRSM-4+IMPX	Max	Top	598.719	99.545	0.004	0.001	0.008
RT	COMBRSM-1-IMPX	Max	Top	598.719	107.086	0.003	0.002	0.009
RT	COMBRSM-2-IMPX	Max	Top	598.719	107.086	0.003	0.001	0.007
RT	COMBRSM-3-IMPX	Max	Top	598.719	107.086	0.003	0.002	0.009
RT	COMBRSM-4-IMPX	Max	Top	598.719	107.086	0.003	0.001	0.007
RL	COMBRSM-1+IMPX	Max	Top	5715.692	513.481	0.005	0.002	0.025
RL	COMBRSM-2+IMPX	Max	Top	5715.692	513.481	0.005	0.002	0.020
RL	COMBRSM-3+IMPX	Max	Top	5715.692	513.481	0.005	0.002	0.025
RL	COMBRSM-4+IMPX	Max	Top	5715.692	513.481	0.005	0.002	0.020
RL	COMBRSM-1-IMPX	Max	Top	5715.692	567.706	0.004	0.002	0.022
RL	COMBRSM-2-IMPX	Max	Top	5715.692	567.706	0.004	0.002	0.018
RL	COMBRSM-3-IMPX	Max	Top	5715.692	567.706	0.004	0.002	0.022
RL	COMBRSM-4-IMPX	Max	Top	5715.692	567.706	0.004	0.002	0.018

Table 5-4 is a summarized drift value of the maximum results obtained per each storey. [X-Max]

Table 5-4 θ_X (Max) governing values for each storey

Story	Combination	P_{tot} [kN]	V_{Xtot}[kN]	$d_{r,X}/h$	θ_X (Max)
RT	COMBRSM-1+IMPX	598.719	99.545	0.002	0.010
RL	COMBRSM-1+IMPX	5715.692	513.481	0.002	0.025
13TH	COMBRSM-1+IMPX	13552.333	824.007	0.003	0.042
12TH	COMBRSM-1+IMPX	21239.608	1000.758	0.003	0.058
11TH	COMBRSM-1+IMPX	28921.089	1106.366	0.003	0.078
10TH	COMBRSM-1+IMPX	36453.577	1183.958	0.003	0.094
9TH	COMBRSM-1+IMPX	44286.777	1258.620	0.003	0.114
8TH	COMBRSM-1+IMPX	52118.046	1332.509	0.003	0.133
7TH	COMBRSM-1+IMPX	59949.315	1399.333	0.004	0.151
6TH	COMBRSM-1+IMPX	67780.583	1459.907	0.004	0.168
5TH	COMBRSM-1+IMPX	75611.852	1525.150	0.004	0.182
4TH	COMBRSM-1+IMPX	83443.121	1607.732	0.004	0.190
3RD	COMBRSM-1+IMPX	91274.389	1712.984	0.004	0.191
2ND	COMBRSM-1+IMPX	99162.543	1841.947	0.003	0.180
1ST	COMBRSM-1+IMPX	92793.108	1903.812	0.002	0.104
GF	COMBRSM-1+IMPX	99499.175	1837.695	0.001	0.037

5.1.1.2.1.2 X-direction Minimum

Total axial force P_{tot}, total story shear V_{tot} and inter story drift ratio d_r/h results are extracted from ETABS analysis software. Results for all seismic related combinations in the X direction and minimum step type are extracted for the purpose of drift sensitivity coefficient determination. Sample extracted data is shown in **Table 5-5** and **Table 5-6**.

Table 5-5 X-Min drift results

Story	Output Case	Case Type	Step Type	Direction	Drift
RT	COMBRSM-1-IMPX	Combination	Min	X	0.0016
RT	COMBRSM-1+IMPX	Combination	Min	X	0.0012
RT	COMBRSM-2+IMPX	Combination	Min	X	0.0016
RT	COMBRSM-2+IMPX	Combination	Min	X	0.0012
RT	COMBRSM-3+IMPX	Combination	Min	X	0.0016
RT	COMBRSM-3+IMPX	Combination	Min	X	0.0012
RT	COMBRSM-4+IMPX	Combination	Min	X	0.0016
RT	COMBRSM-4+IMPX	Combination	Min	X	0.0012
RT	COMBRSM-1-IMPX	Combination	Min	X	0.0012
RT	COMBRSM-1-IMPX	Combination	Min	X	0.0016
RT	COMBRSM-2-IMPX	Combination	Min	X	0.0012
RT	COMBRSM-2-IMPX	Combination	Min	X	0.0016
RT	COMBRSM-3-IMPX	Combination	Min	X	0.0012

Table 5-6 X-Min story forces

Story	Output Case	Case Type	Step Type	Location	P	VX
					kN	kN
RT	COMBRSM-1+IMPX	Combination	Min	Top	598.7187	-107.0856
RT	COMBRSM-1+IMPX	Combination	Min	Bottom	896.2438	-107.0856
RT	COMBRSM-2+IMPX	Combination	Min	Top	598.7187	-107.0856
RT	COMBRSM-2+IMPX	Combination	Min	Bottom	896.2438	-107.0856
RT	COMBRSM-3+IMPX	Combination	Min	Top	598.7187	-107.0856
RT	COMBRSM-3+IMPX	Combination	Min	Bottom	896.2438	-107.0856
RT	COMBRSM-4+IMPX	Combination	Min	Top	598.7187	-107.0856
RT	COMBRSM-4+IMPX	Combination	Min	Bottom	896.2438	-107.0856
RT	COMBRSM-1-IMPX	Combination	Min	Top	598.7187	-99.5452
RT	COMBRSM-1-IMPX	Combination	Min	Bottom	896.2438	-99.5452
RT	COMBRSM-2-IMPX	Combination	Min	Top	598.7187	-99.5452
RT	COMBRSM-2-IMPX	Combination	Min	Bottom	896.2438	-99.5452

Now that the analysis results required for the determination of drift sensitivity coefficient are extracted, θ values for each storey and each combination can be calculated. Sample inter storey drift calculation for all stories and all combinations in the X-Min direction of the sample building is presented on **Table 5-7**.

Table 5-7 θ_X (Min) for all combinations

Story	Output Case	Step Type	Location	P	V_X	ds_X* q	de_X	θ_X (Min)
				kN	kN			
RT	COMBRSM-1+IMPX	Min	Top	598.719	-107.086	0.003	0.001	0.007
RT	COMBRSM-2+IMPX	Min	Top	598.719	-107.086	0.003	0.002	0.009
RT	COMBRSM-3+IMPX	Min	Top	598.719	-107.086	0.003	0.001	0.007
RT	COMBRSM-4+IMPX	Min	Top	598.719	-107.086	0.003	0.002	0.009
RT	COMBRSM-1-IMPX	Min	Top	598.719	-99.545	0.004	0.001	0.008
RT	COMBRSM-2-IMPX	Min	Top	598.719	-99.545	0.004	0.002	0.010
RT	COMBRSM-3-IMPX	Min	Top	598.719	-99.545	0.004	0.001	0.008
RT	COMBRSM-4-IMPX	Min	Top	598.719	-99.545	0.004	0.002	0.010
RL	COMBRSM-1+IMPX	Min	Top	5715.692	-567.706	0.004	0.002	0.018
RL	COMBRSM-2+IMPX	Min	Top	5715.692	-567.706	0.004	0.002	0.022
RL	COMBRSM-3+IMPX	Min	Top	5715.692	-567.706	0.004	0.002	0.018
RL	COMBRSM-4+IMPX	Min	Top	5715.692	-567.706	0.004	0.002	0.022
RL	COMBRSM-1-IMPX	Min	Top	5715.692	-513.481	0.005	0.002	0.020
RL	COMBRSM-2-IMPX	Min	Top	5715.692	-513.481	0.005	0.002	0.025

Table 5-8 is a summarized drift value of the maximum results obtained per each storey. [X-Min]

Table 5-8 θ_X (Min) governing values for each storey

Story	Combination	P_{tot} [kN]	V_{Xtot}[kN]	$d_{r,X}/h$	θ_X (Min)
RT	COMBRSM-1-IMPX	598.719	-99.545	0.002	0.010
RL	COMBRSM-1-IMPX	5715.692	-513.481	0.002	0.025
13TH	COMBRSM-1-IMPX	13552.333	-824.007	0.003	0.042
12TH	COMBRSM-1-IMPX	21239.608	-1000.758	0.003	0.058
11TH	COMBRSM-1-IMPX	28921.089	-1106.366	0.003	0.077
10TH	COMBRSM-1-IMPX	36453.577	-1183.958	0.003	0.093
9TH	COMBRSM-1-IMPX	44286.777	-1258.620	0.003	0.112
8TH	COMBRSM-1-IMPX	52118.046	-1332.509	0.003	0.130
7TH	COMBRSM-1-IMPX	59949.315	-1399.333	0.003	0.148
6TH	COMBRSM-1-IMPX	67780.583	-1459.907	0.004	0.165
5TH	COMBRSM-1-IMPX	75611.852	-1525.150	0.004	0.179
4TH	COMBRSM-1-IMPX	83443.121	-1607.732	0.004	0.187
3RD	COMBRSM-1-IMPX	91274.389	-1712.984	0.004	0.187
2ND	COMBRSM-1-IMPX	99162.543	-1841.947	0.003	0.173
1ST	COMBRSM-1-IMPX	91014.676	-1891.271	0.002	0.091
GF	COMBRSM-1-IMPX	97513.543	-1832.127	0.000	0.014

5.1.1.2.1.3 Y-direction Maximum

Total axial force P_{tot}, total story shear V_{tot} and inter story drift ratio d_r/h results are extracted from ETABS analysis software. Results for all seismic related combinations in the Y direction and maximum step type are extracted for the purpose of drift sensitivity coefficient determination. Sample extracted data is shown in **Table 5-9** and **Table 5-10**.

Table 5-9 Y-Max drift results

Story	Output Case	Case Type	Step Type	Direction	Drift
RT	COMBRSM-5+IMPY	Combination	Max	Y	0.0010
RT	COMBRSM-6+IMPY	Combination	Max	Y	0.0010
RT	COMBRSM-7+IMPY	Combination	Max	Y	0.0010
RT	COMBRSM-8+IMPY	Combination	Max	Y	0.0010
RT	COMBRSM-5-IMPY	Combination	Max	Y	0.0007
RT	COMBRSM-6-IMPY	Combination	Max	Y	0.0007
RT	COMBRSM-7-IMPY	Combination	Max	Y	0.0007
RT	COMBRSM-8-IMPY	Combination	Max	Y	0.0007
RT	COMBRSM-5+IMPY E	Combination	Max	Y	0.0021
RT	COMBRSM-5-IMPY E	Combination	Max	Y	0.0018
RT	COMBRSM-6+IMPY E	Combination	Max	Y	0.0021
RT	COMBRSM-6-IMPY E	Combination	Max	Y	0.0018
RT	COMBRSM-7+IMPY E	Combination	Max	Y	0.0021

Table 5-10 Y-Max story forces

Story	Output Case	Case Type	Step Type	Location	P	VY
					kN	kN
RT	COMBRSM-5+IMPY	Combination	Max	Top	598.7188	83.8566
RT	COMBRSM-5+IMPY	Combination	Max	Bottom	896.2438	83.8566
RT	COMBRSM-6+IMPY	Combination	Max	Top	598.7188	83.8566
RT	COMBRSM-6+IMPY	Combination	Max	Bottom	896.2438	83.8566
RT	COMBRSM-7+IMPY	Combination	Max	Top	598.7188	83.8566
RT	COMBRSM-7+IMPY	Combination	Max	Bottom	896.2438	83.8566
RT	COMBRSM-8+IMPY	Combination	Max	Top	598.7188	83.8566
RT	COMBRSM-8+IMPY	Combination	Max	Bottom	896.2438	83.8566
RT	COMBRSM-5-IMPY	Combination	Max	Top	598.7188	91.3971
RT	COMBRSM-5-IMPY	Combination	Max	Bottom	896.2438	91.3971
RT	COMBRSM-6-IMPY	Combination	Max	Top	598.7188	91.3971

Now that the analysis results required for the determination of drift sensitivity coefficient are extracted, θ values for each storey and each combination can be calculated. Sample inter storey drift calculation for all stories and all combinations in the Y-Max direction of the sample building is presented on **Table 5-11**.

Table 5-11 θ_y (Max) for all combinations

Story	Output Case	Step Type	Location	P	V_y	ds_y* q	de_y	θ_y (Max)
				kN	kN			
RT	COMBRSM-5+IMPY	Max	Top	598.719	83.857	0.002	0.002	0.015
RT	COMBRSM-6+IMPY	Max	Top	598.719	83.857	0.002	0.002	0.013
RT	COMBRSM-7+IMPY	Max	Top	598.719	83.857	0.002	0.002	0.015
RT	COMBRSM-8+IMPY	Max	Top	598.719	83.857	0.002	0.002	0.013
RT	COMBRSM-5-IMPY	Max	Top	598.719	91.397	0.002	0.002	0.011
RT	COMBRSM-6-IMPY	Max	Top	598.719	91.397	0.002	0.002	0.011
RT	COMBRSM-7-IMPY	Max	Top	598.719	91.397	0.002	0.002	0.011
RT	COMBRSM-8-IMPY	Max	Top	598.719	91.397	0.002	0.002	0.011
RL	COMBRSM-5+IMPY	Max	Top	5715.692	483.269	0.003	0.003	0.031
RL	COMBRSM-6+IMPY	Max	Top	5715.692	483.269	0.003	0.002	0.028
RL	COMBRSM-7+IMPY	Max	Top	5715.692	483.269	0.003	0.003	0.031
RL	COMBRSM-8+IMPY	Max	Top	5715.692	483.269	0.003	0.002	0.028
RL	COMBRSM-5-IMPY	Max	Top	5715.692	537.494	0.002	0.003	0.024
RL	COMBRSM-6-IMPY	Max	Top	5715.692	537.494	0.002	0.002	0.024

Table 5-12 is a summarized drift value of the maximum results obtained per each storey. [Y-Max]

Table 5-12 θ_y (Max) governing values for each storey

Story	Combination	P_{tot} [kN]	V_{ytot}[kN]	$d_{r,y}/h$	θ_Y (Max)
RT	COMBRSM-5+IMPY	598.719	83.857	0.002	0.015
RL	COMBRSM-5+IMPY	5715.692	483.269	0.003	0.031
13TH	COMBRSM-5+IMPY	13552.333	782.903	0.003	0.050
12TH	COMBRSM-5+IMPY	21239.608	963.222	0.003	0.068
11TH	COMBRSM-5+IMPY	28921.089	1068.223	0.003	0.088
10TH	COMBRSM-5+IMPY	36453.577	1137.869	0.003	0.112
9TH	COMBRSM-5+IMPY	44286.777	1196.207	0.004	0.138
8TH	COMBRSM-5+IMPY	52118.046	1251.539	0.004	0.166
7TH	COMBRSM-5+IMPY	59949.315	1310.395	0.004	0.191
6TH	COMBRSM-5+IMPY	67780.583	1379.118	0.004	0.214
5TH	COMBRSM-5+IMPY	75611.852	1460.496	0.005	0.233
4TH	COMBRSM-5+IMPY	83443.121	1555.723	0.005	0.246
3RD	COMBRSM-5+IMPY	91274.389	1663.646	0.005	0.250
2ND	COMBRSM-5+IMPY	99162.543	1783.181	0.004	0.234
1ST	COMBRSM-5+IMPY	93001.335	1804.316	0.003	0.131
GF	COMBRSM-5+IMPY	100359.604	1721.674	0.000	0.016

5.1.1.2.1.4 Y-direction Minimum

Total axial force P_{tot}, total story shear V_{tot} and inter story drift ratio results are extracted from ETABS analysis software. Results for all seismic related combinations in the Y direction and minimum step type are extracted for the purpose of drift sensitivity coefficient determination. Sample extracted data is shown in **Table 5-13** and **Table 5-14**.

Table 5-13 Y-Min drift results

Story	Output Case	Case Type	Step Type	Direction	Drift
RT	COMBRSM-5+IMPY	Combination	Min	Y	0.0011
RT	COMBRSM-6+IMPY	Combination	Min	Y	0.0011
RT	COMBRSM-7+IMPY	Combination	Min	Y	0.0011
RT	COMBRSM-8+IMPY	Combination	Min	Y	0.0011
RT	COMBRSM-5-IMPY	Combination	Min	Y	0.0013
RT	COMBRSM-6-IMPY	Combination	Min	Y	0.0013
RT	COMBRSM-7-IMPY	Combination	Min	Y	0.0013
RT	COMBRSM-8-IMPY	Combination	Min	Y	0.0013
RT	COMBRSM-5+IMPY E	Combination	Min	Y	0.0021
RT	COMBRSM-5-IMPY E	Combination	Min	Y	0.0024
RT	COMBRSM-6+IMPY E	Combination	Min	Y	0.0021
RT	COMBRSM-6-IMPY E	Combination	Min	Y	0.0024
RT	COMBRSM-7+IMPY E	Combination	Min	Y	0.0021

Table 5-14 Y-Min story forces

Story	Output Case	Case Type	Step Type	Location	P	VY
					kN	kN
RT	COMBRSM-5+IMPY	Combination	Min	Top	598.7187	-91.3971
RT	COMBRSM-5+IMPY	Combination	Min	Bottom	896.2438	-91.3971
RT	COMBRSM-6+IMPY	Combination	Min	Top	598.7187	-91.3971
RT	COMBRSM-6+IMPY	Combination	Min	Bottom	896.2438	-91.3971
RT	COMBRSM-7+IMPY	Combination	Min	Top	598.7187	-91.3971
RT	COMBRSM-7+IMPY	Combination	Min	Bottom	896.2438	-91.3971
RT	COMBRSM-8+IMPY	Combination	Min	Top	598.7187	-91.3971
RT	COMBRSM-8+IMPY	Combination	Min	Bottom	896.2438	-91.3971
RT	COMBRSM-5-IMPY	Combination	Min	Top	598.7187	-83.8566
RT	COMBRSM-5-IMPY	Combination	Min	Bottom	896.2438	-83.8566
RT	COMBRSM-6-IMPY	Combination	Min	Top	598.7187	-83.8566
RT	COMBRSM-6-IMPY	Combination	Min	Bottom	896.2438	-83.8566

Now that the analysis results required for the determination of drift sensitivity coefficient are extracted, θ values for each storey and each combination can be calculated. Sample inter storey drift calculation for all stories and all combinations in the Y-Min direction of the sample building is presented on **Table 5-15**.

Table 5-15 θ_y (Min) for all combinations

Story	Output Case	Step Type	Location	P	V_y	ds_y* q	de_y	θ_Y (Min)
				kN	kN			
RT	COMBRSM-5+IMPY	Min	Top	598.719	-91.397	0.003	0.002	0.014
RT	COMBRSM-6+IMPY	Min	Top	598.719	-91.397	0.003	0.002	0.016
RT	COMBRSM-7+IMPY	Min	Top	598.719	-91.397	0.003	0.002	0.014
RT	COMBRSM-8+IMPY	Min	Top	598.719	-91.397	0.003	0.002	0.016
RT	COMBRSM-5-IMPY	Min	Top	598.719	-83.857	0.003	0.002	0.015
RT	COMBRSM-6-IMPY	Min	Top	598.719	-83.857	0.003	0.002	0.017
RT	COMBRSM-7-IMPY	Min	Top	598.719	-83.857	0.003	0.002	0.015
RT	COMBRSM-8-IMPY	Min	Top	598.719	-83.857	0.003	0.002	0.017
RL	COMBRSM-5+IMPY	Min	Top	5715.692	-537.494	0.003	0.003	0.030
RL	COMBRSM-6+IMPY	Min	Top	5715.692	-537.494	0.003	0.003	0.033
RL	COMBRSM-7+IMPY	Min	Top	5715.692	-537.494	0.003	0.003	0.030
RL	COMBRSM-8+IMPY	Min	Top	5715.692	-537.494	0.003	0.003	0.033
RL	COMBRSM-5-IMPY	Min	Top	5715.692	-483.269	0.004	0.003	0.033
RL	COMBRSM-6-IMPY	Min	Top	5715.692	-483.269	0.004	0.003	0.036

Table 5-16 is a summarized drift value of the maximum results obtained per each storey. [Y-Min]

Table 5-16 θ_y (Min) governing values for each storey

Story	Combination	P_{tot} [kN]	V_{Ytot}[kN]	$d_{r,Y}/h$	θ_Y (Min)
RT	COMBRSM-5-IMPY	598.719	-83.857	0.002	0.017
RL	COMBRSM-5-IMPY	5715.692	-483.269	0.003	0.036
13TH	COMBRSM-5-IMPY	13552.333	-782.903	0.003	0.057
12TH	COMBRSM-5-IMPY	21239.608	-963.222	0.004	0.078
11TH	COMBRSM-5-IMPY	28921.089	-1068.223	0.004	0.099
10TH	COMBRSM-5-IMPY	36453.577	-1137.869	0.004	0.121
9TH	COMBRSM-5-IMPY	44286.777	-1196.207	0.004	0.149
8TH	COMBRSM-5-IMPY	52118.046	-1251.539	0.004	0.178
7TH	COMBRSM-5-IMPY	59949.315	-1310.395	0.004	0.204
6TH	COMBRSM-5-IMPY	67780.583	-1379.118	0.005	0.227
5TH	COMBRSM-5-IMPY	75611.852	-1460.496	0.005	0.245
4TH	COMBRSM-5-IMPY	83443.121	-1555.723	0.005	0.254
3RD	COMBRSM-5-IMPY	91274.389	-1663.646	0.005	0.253
2ND	COMBRSM-5-IMPY	99162.543	-1783.181	0.004	0.228
1ST	COMBRSM-5-IMPY	90806.448	-1831.455	0.002	0.124
GF	COMBRSM-5-IMPY	96653.113	-1804.558	0.000	0.014

5.1.1.2.2 Program results

The program only asks the user for the behaviour factor of the building under consideration. The behaviour factor is calculated according to code recommendation for and it amounts to 2.4. The user is also provided with the opportunity to choose the load combinations for which stability analysis has to be done. **Figure 5-5** shows input data fed into the program.

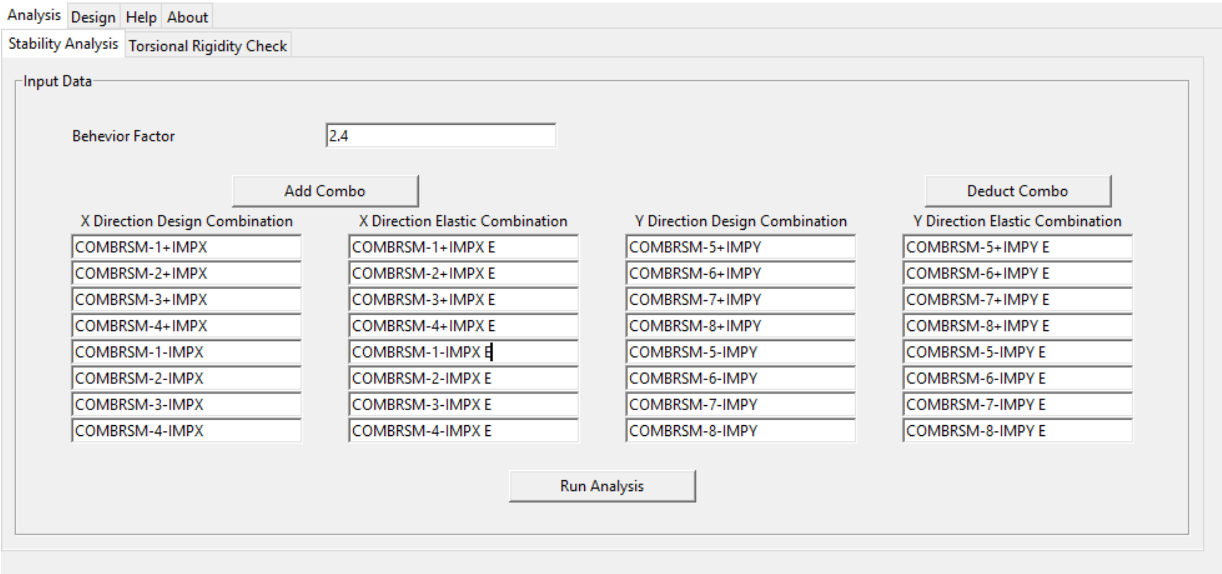


Figure 5-5 Input data for torsional stability analysis

By interacting to the open instance of ETABS model through the API, the program analysed the model for lateral stability. Required input data from the user is also made available to the program through the developed user interface. Analysis results from the program are shown on **Figure 5-6** to **Figure 5-9**.

X Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	X	Max	COMBRSM-1+IMPX	0.010056655684605608	Good
RL	X	Max	COMBRSM-1+IMPX	0.02465886517718323	Good
13TH	X	Max	COMBRSM-1+IMPX	0.041564007911478046	Good
12TH	X	Max	COMBRSM-1+IMPX	0.058428385941022946	Good
11TH	X	Max	COMBRSM-1+IMPX	0.0777019469931057	Good
10TH	X	Max	COMBRSM-1+IMPX	0.09403870089516003	Good
9TH	X	Max	COMBRSM-1+IMPX	0.11371579738785353	P-Delta required
8TH	X	Max	COMBRSM-1+IMPX	0.13263574002727502	P-Delta required
7TH	X	Max	COMBRSM-1+IMPX	0.15098693923168047	P-Delta required
6TH	X	Max	COMBRSM-1+IMPX	0.16815630693258213	P-Delta required
5TH	X	Max	COMBRSM-1+IMPX	0.18215060104297973	P-Delta required
4TH	X	Max	COMBRSM-1+IMPX	0.190425049550279	P-Delta required
3RD	X	Max	COMBRSM-1+IMPX	0.19066525475218077	P-Delta required
2ND	X	Max	COMBRSM-1+IMPX	0.18043663391360248	P-Delta required
1ST	X	Max	COMBRSM-1+IMPX	0.10351337568519375	P-Delta required
GF	X	Max	COMBRSM-1+IMPX	0.03675699221207128	Good

Figure 5-6 Stability analysis results from the program (X-Max)

X Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	X	Min	COMBRSM-1-IMPX	0.010036576639434917	Good
RL	X	Min	COMBRSM-1-IMPX	0.024696034914784802	Good
13TH	X	Min	COMBRSM-1-IMPX	0.04152107783411868	Good
12TH	X	Min	COMBRSM-1-IMPX	0.05825199933798478	Good
11TH	X	Min	COMBRSM-1-IMPX	0.07723963475271489	Good
10TH	X	Min	COMBRSM-1-IMPX	0.09330526868261217	Good
9TH	X	Min	COMBRSM-1-IMPX	0.11217926847996815	P-Delta required
8TH	X	Min	COMBRSM-1-IMPX	0.1303595962350173	P-Delta required
7TH	X	Min	COMBRSM-1-IMPX	0.1483121041178837	P-Delta required
6TH	X	Min	COMBRSM-1-IMPX	0.16530453679761786	P-Delta required
5TH	X	Min	COMBRSM-1-IMPX	0.17928521453753865	P-Delta required
4TH	X	Min	COMBRSM-1-IMPX	0.1874717141738309	P-Delta required
3RD	X	Min	COMBRSM-1-IMPX	0.18713451509650575	P-Delta required
2ND	X	Min	COMBRSM-1-IMPX	0.17283088138453867	P-Delta required
1ST	X	Min	COMBRSM-1-IMPX	0.09303640902854246	Good
GF	X	Min	COMBRSM-1-IMPX	0.014180567788598294	Good

Figure 5-7 Stability analysis results from the program (X-Min)

Y Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	Y	Max	COMBRSM-5+IMPY	0.014644428197212428	Good
RL	Y	Max	COMBRSM-5+IMPY	0.031143482440339248	Good
13TH	Y	Max	COMBRSM-5+IMPY	0.04970824518486439	Good
12TH	Y	Max	COMBRSM-5+IMPY	0.06825175830143253	Good
11TH	Y	Max	COMBRSM-5+IMPY	0.08842348150319074	Good
10TH	Y	Max	COMBRSM-5+IMPY	0.11166941096738739	P-Delta required
9TH	Y	Max	COMBRSM-5+IMPY	0.1384797650454725	P-Delta required
8TH	Y	Max	COMBRSM-5+IMPY	0.16551284057939172	P-Delta required
7TH	Y	Max	COMBRSM-5+IMPY	0.1913371563489852	P-Delta required
6TH	Y	Max	COMBRSM-5+IMPY	0.21434234225630083	P-Delta required
5TH	Y	Max	COMBRSM-5+IMPY	0.2330219957874542	P-Delta required
4TH	Y	Max	COMBRSM-5+IMPY	0.24567284109591925	P-Delta required
3RD	Y	Max	COMBRSM-5+IMPY	0.24993271660908983	P-Delta required
2ND	Y	Max	COMBRSM-5+IMPY	0.23381803459403108	P-Delta required
1ST	Y	Max	COMBRSM-5+IMPY	0.13069182276834254	P-Delta required
GF	Y	Max	COMBRSM-5+IMPY	0.015919783477158923	Good

Figure 5-8 Stability analysis results from the program (Y-Max)

Y Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	Y	Min	COMBRSM-5-IMPY	0.017072756107376737	Good
RL	Y	Min	COMBRSM-5-IMPY	0.036460077623672524	Good
13TH	Y	Min	COMBRSM-5-IMPY	0.057426303991659614	Good
12TH	Y	Min	COMBRSM-5-IMPY	0.07763660378628398	Good
11TH	Y	Min	COMBRSM-5-IMPY	0.09865657784924924	Good
10TH	Y	Min	COMBRSM-5-IMPY	0.12110275838678852	P-Delta required
9TH	Y	Min	COMBRSM-5-IMPY	0.14944980551672735	P-Delta required
8TH	Y	Min	COMBRSM-5-IMPY	0.17754932953713787	P-Delta required
7TH	Y	Min	COMBRSM-5-IMPY	0.20405961614749193	P-Delta required
6TH	Y	Min	COMBRSM-5-IMPY	0.22704689779307255	P-Delta required
5TH	Y	Min	COMBRSM-5-IMPY	0.24463378807522596	P-Delta required
4TH	Y	Min	COMBRSM-5-IMPY	0.25444309555360334	P-Delta required
3RD	Y	Min	COMBRSM-5-IMPY	0.252855504956242	P-Delta required
2ND	Y	Min	COMBRSM-5-IMPY	0.22747771986474757	P-Delta required
1ST	Y	Min	COMBRSM-5-IMPY	0.12656657483111539	P-Delta required
GF	Y	Min	COMBRSM-5-IMPY	0.014682690362302709	Good

Figure 5-9 Stability analysis results from the program (Y-Min)

5.1.1.2.3 Stability analysis results comparison

As both the developed program and the executed manual calculation followed standard procedures recommended by the building design code, deviation between output results is not expected. Summary of comparison between manual analysis and program analysis is shown on **Table 5-17** and **Table 5-18**.

Table 5-17 Comparison on stability analysis results (X-direction)

Story	Manual analysis		Program analysis		Remark	
	θ (X-Max)	θ (X-Min)	θ (X-Max)	θ (X-Min)	θ (X-Max)	θ (X-Min)
RT	0.01006	0.01004	0.01006	0.01004	Ok	Ok
RL	0.02466	0.02470	0.02466	0.02470	Ok	Ok
13^{TH}	0.04156	0.04152	0.04156	0.04152	Ok	Ok
12^{TH}	0.05843	0.05825	0.05843	0.05825	Ok	Ok
11^{TH}	0.07770	0.07724	0.07770	0.07724	Ok	Ok
10^{TH}	0.09404	0.09331	0.09404	0.09331	Ok	Ok
9^{TH}	0.11372	0.11218	0.11372	0.11218	Ok	Ok
8^{TH}	0.13264	0.13036	0.13264	0.13036	Ok	Ok
7^{TH}	0.15099	0.14831	0.15099	0.14831	Ok	Ok
6^{TH}	0.16816	0.16530	0.16816	0.16530	Ok	Ok
5^{TH}	0.18215	0.17929	0.18215	0.17929	Ok	Ok
4^{TH}	0.19043	0.18747	0.19043	0.18747	Ok	Ok
3^{RD}	0.19042	0.18713	0.19042	0.18713	Ok	Ok
2^{ND}	0.18044	0.17283	0.18044	0.17283	Ok	Ok
1^{ST}	0.10351	0.09304	0.10351	0.09304	Ok	Ok
GF	0.03676	0.01418	0.03676	0.01418	Ok	Ok

Table 5-18 Comparison on stability analysis results (Y-direction)

Story	Manual analysis		Program analysis		% difference	
	θ (Y-Max)	θ (Y-Min)	θ (Y-Max)	θ (Y-Min)	θ (Y-Max)	θ (Y-Min)
RT	0.01464	0.01707	0.01464	0.01707	Ok	Ok
RL	0.03114	0.03646	0.03114	0.03646	Ok	Ok
13TH	0.05971	0.05743	0.05971	0.05743	Ok	Ok
12TH	0.06825	0.07764	0.06825	0.07764	Ok	Ok
11TH	0.08842	0.09866	0.08842	0.09866	Ok	Ok
10TH	0.11167	0.12110	0.11167	0.12110	Ok	Ok
9TH	0.13848	0.14945	0.13848	0.14945	Ok	Ok
8TH	0.16551	0.17755	0.16551	0.17755	Ok	Ok
7TH	0.19134	0.20406	0.19134	0.20406	Ok	Ok
6TH	0.21434	0.22705	0.21434	0.22705	Ok	Ok
5TH	0.23302	0.24463	0.23302	0.24463	Ok	Ok
4TH	0.24567	0.25444	0.24567	0.25444	Ok	Ok
3RD	0.24993	0.25286	0.24993	0.25286	Ok	Ok
2ND	0.23382	0.22748	0.23382	0.22748	Ok	Ok
1ST	0.13069	0.12657	0.13069	0.12657	Ok	Ok
GF	0.01592	0.01468	0.01592	0.01468	Ok	Ok

5.1.1.3 Torsional rigidity analysis

The manual analysis and the analysis using the developed program are both performed to check the torsional rigidity of the building under consideration. The torsional rigidity of the building is checked by using code recommended procedure. The results of the manual analysis and the analysis using the developed program are then compared to ensure that the program accurately and reliably predicts the torsional rigidity of the building.

5.1.1.3.1 Manual calculation for torsional rigidity

The manual calculation for torsional rigidity is done following multiple procedural steps. Each step is done following provisions of the code and are presented here.

5.1.1.3.1.1 Calculation of the center of stiffness

For the determination of parameters required for the determination of torsional rigidity, analysis of the building model have to be performed for loads applied on the center of stiffness of each floor. ETABS analysis software is used for the determination of the center of stiffness of the building model. **Table 5-19** presents the center of mass and center of stiffness of the building model. The values represent the distance between the center of mass and the center of rigidity of the model, referenced from the origin of the coordinate system of the model.

Table 5-19 Center of mass and Center of stiffness

Story	Diaphragm	Center of mass X (m)	Center of mass (Y) (m)	Center of stiffness (X) (m)	Center of stiffness (Y) (m)
GF	GF	9.72	12.11	11.30	16.94
1ST	1ST	8.24	11.61	7.06	11.12
2ND	2ND	9.19	9.72	7.03	10.68
3RD	3RD	9.23	9.81	7.08	10.56
4TH	4TH	9.23	9.81	7.14	10.52
5TH	5TH	9.23	9.81	7.22	10.50
6TH	6TH	9.23	9.81	7.30	10.50
7TH	7TH	9.23	9.81	7.39	10.50
8TH	8TH	9.23	9.81	7.48	10.51
9TH	9TH	9.23	9.81	7.58	10.53
10TH	10TH	9.07	9.99	7.68	10.55
11TH	11TH	9.08	9.91	7.80	10.61
12TH	12TH	9.08	9.91	7.92	10.68
13TH	13TH	9.00	9.91	8.04	10.77
RL	RL	9.09	9.97	8.18	10.89
RT	RT	8.85	14.14	8.41	10.86

5.1.1.3.1.2 Defining load cases

Load cases have to be defined for all the three types of loads that are to be applied on a single floor of the building. This have to be done for each and every one of the floors for which torsional rigidity analysis is to be done. The three load types to be applied on the center of rigidity of the building are X direction force, Y direction force and rotational moment in the Z direction. For this specific case, as we have 16 floors in total, 48 load cases have to be defined. **Table 5-20** shows an organized outline of the defined load cases.

Table 5-20 Defined load cases

Story	X-direction load case	Y-direction load case	Z-direction load case
GF	GF_X	GF_Y	GF_Z
1^{ST}	1^{ST}_X	1^{ST}_Y	1^{ST}_Z
2^{ND}	2^{ND}_X	2^{ND}_Y	2^{ND}_Z
3^{RD}	3^{RD}_X	3^{RD}_Y	3^{RD}_Z
4^{TH}	4^{TH}_X	4^{TH}_Y	4^{TH}_Z
5^{TH}	5^{TH}_X	5^{TH}_Y	5^{TH}_Z
6^{TH}	6^{TH}_X	6^{TH}_Y	6^{TH}_Z
7^{TH}	7^{TH}_X	7^{TH}_Y	7^{TH}_Z
8^{TH}	8^{TH}_X	8^{TH}_Y	8^{TH}_Z
9^{TH}	9^{TH}_X	9^{TH}_Y	9^{TH}_Z
10^{TH}	10^{TH}_X	10^{TH}_Y	10^{TH}_Z
11^{TH}	11^{TH}_X	11^{TH}_Y	11^{TH}_Z
12^{TH}	12^{TH}_X	12^{TH}_Y	12^{TH}_Z
13^{TH}	13^{TH}_X	13^{TH}_Y	13^{TH}_Z
RL	RL_X	RL_Y	RL_Z
RT	RT_X	RT_Y	RT_Z

5.1.1.3.1.3 Defining point objects and assigning diaphragm

On this step, new point objects are introduced into the system. These newly defined points are created on the center of rigidity of the model for every floor. Center of rigidity data is taken from step one of this example calculation. Created point objects are then assigned with the diaphragm assignment of the floor they are created on. This is done to make sure that the point objects are moving along with the model and not freely. These joints are assigned with a unique name showing the floor at which they are created. **Table 5-21** shows the coordinate at which the point objects are created, story level, diaphragm name and the unique name they are assigned with.

Table 5-21 Point object definition

Story	X-coordinate	Y-coordinate	Unique name	Diaphragm
GF	11.30	16.94	GFCR	GF
1^{ST}	7.06	11.12	1STCR	1^{ST}
2^{ND}	7.03	10.68	2NDCR	2^{ND}
3^{RD}	7.08	10.56	3RDCR	3^{RD}
4^{TH}	7.14	10.52	4THCR	4^{TH}
5^{TH}	7.22	10.50	5THCR	5^{TH}
6^{TH}	7.30	10.50	6THCR	6^{TH}
7^{TH}	7.39	10.50	7THCR	7^{TH}
8^{TH}	7.48	10.51	8THCR	8^{TH}
9^{TH}	7.58	10.53	9THCR	9^{TH}
10^{TH}	7.68	10.55	10THCR	10^{TH}
11^{TH}	7.80	10.61	11THCR	11^{TH}
12^{TH}	7.92	10.68	12THCR	12^{TH}
13^{TH}	8.04	10.77	13THCR	13^{TH}
RL	8.18	10.89	RLCR	RL
RT	8.41	10.86	RTCR	RT

5.1.1.3.1.4 Load application

On this step load is applied on the created point objects. Force with a magnitude of 1000000kN is applied both in the X and Y directions. In addition to that, a rotational moment of 1000000kNm is applied on the joints. The load case used for the assignment of these loads has to be specifically selected floor the point object is created on and the type of the force applied.

5.1.1.3.1.5 Result extraction and calculation of torsional radius

To get the data required for the calculation of required parameters, analysis results from the model are extracted for each defined load cases. Story displacement in the X direction, Y direction and rotation in the Z direction are extracted for each story and corresponding load case. Stiffness value of each floor is then calculated using equations 5-2 to 5-4.

$$K_{m,i} = \frac{1}{R_{Z,i}(M_{T,i} = 1000000kNm)} \quad (5\text{-}2)$$

$$K_{FX,i} = \frac{1}{U_{X,i}(F_{TX,i} = 1000000kN)} \quad (5\text{-}3)$$

$$K_{FY,i} = \frac{1}{U_{Y,i}(F_{TY,i} = 1000000kN)} \quad (5\text{-}4)$$

where :

$K_{m,i}$ is the torsional stiffness of the i^{th} floor

$K_{FX,i}$ is the lateral stiffness of the i^{th} floor in the X *direction*

$K_{FY,i}$ is the lateral stiffness of the i^{th} floor in the Y direction

$R_{Z,i}$ is the rotational displacement of the i^{th} floor for a moment ($M_{T,i} = 1000000 kNm$) applied at the center of stiffness of the i^{th} floor

$U_{X,i}$ is the X direction displacement of the i^{th} floor for a load ($F_{TX,i} = 1000000 kN$) applied at the center of stiffness of the i^{th} floor, and

$U_{Y,i}$ is the Y direction displacement of the i^{th} floor for a load ($F_{TY,i} = 1000000 kN$) applied at the center of stiffness of the i^{th} floor

The torsional radius values in both directions are then calculated from the stiffness values using equation 5-5 and 5-6.

$$r_{X,i} = \sqrt{\frac{K_{M,i}}{K_{FY,i}}} \tag{5-5}$$

$$r_{Y,i} = \sqrt{\frac{K_{M,i}}{K_{FX,i}}} \tag{5-6}$$

where :

$r_{X,i}$ is the torsional radius of the i^{th} floor in the X direction

$K_{M,i}$ is the torsional stiffness of the i^{th} floor

$K_{FY,i}$ is the lateral stiffness of the i^{th} floor in the Y *direction*

$r_{Y,i}$ is the torsional radius of the i^{th} floor in the Y direction, *and*

$K_{FX,i}$ is the lateral stiffness of the i^{th} floor in the X *direction*

The radius of gyration of the floor mass in plan is calculated as the square root of the ratio of the polar moment of inertia of the floor mass in plan with respect to the area of the floor mass. For a rectangular floor plan with uniformly distributed load, the radius of gyration can be calculated as:

$$l_s = \sqrt{\frac{l^2 + b^2}{12}} \tag{5-7}$$

where:

l_s is the polar radius of gyration of the floor mass in plan?
l is the length of the floor mass, and?
b is the width of the floor mass

For the ground floor of the building, X direction translational stiffness ($K_{FX,i}$), Y direction translational stiffness ($K_{FY,i}$), Z direction rotational stiffness ($R_{Z,i}$), X direction torsional radius ($r_{X,i}$) and Y direction torsional radius ($r_{Y,i}$) are calculated following the procedure shown below.

Stiffness values

From equation 5-2

$$K_{m,GF} = \frac{1}{R_{Z,GF}(M_{T,GF} = 1000000kNm)} = \frac{1}{0.000383\,rad} = 2610.9661\, kNm/rad$$

From equation 5-3

$$K_{FX,GF} = \frac{1}{U_{X,GF}(F_{TX,GF} = 1000000kN)} = \frac{1}{55.125mm} = 18.1405\, kN/m$$

From equation 5-4

$$K_{FY,GF} = \frac{1}{U_{Y,GF}(F_{TY,GF} = 1000000kN)} = \frac{1}{40.6010mm} = 24.6299 \, {kN}/{m}$$

Torsional radius values

From equation 5-5

$$r_{X,GF} = \sqrt{\frac{K_{M,GF}}{K_{FY,GF}}} = \sqrt{\frac{2610.9661}{24.6299}} = 10.2960m$$

From equation 5-6

$$r_{Y,i} = \sqrt{\frac{K_{M,i}}{K_{FX,i}}} = \sqrt{\frac{2610.9661}{18.1406}} = 11.9971m$$

For the building under consideration, radius of gyration for the typical floor plans is calculated as follows.

Typical floors above the ground level:

$$l_s = \sqrt{\frac{l^2 + b^2}{12}} = \sqrt{\frac{18.2^2 + 22.9^2}{12}} = 8.444$$

All the parametric values required for checking torsional rigidity of the other floors are then calculated following the same procedure and results are presented in **Table 5-22** and **Table 5-23**.

Table 5-22 Summary of torsional radius (r_y)

Story	Load case	U_x(mm)	K_{Fx}	Load case	R_z(rad)	K_M	r_y	l_s	$r_y>l_s$
GF	GF_X	55.13	18.14	GF_Z	0.00	2610.97	12.00	8.44	ok
1ST	1ST_X	646.27	1.55	1ST_Z	0.01	106.89	8.31	8.44	warning!
2ND	2ND_X	2450.43	0.41	2ND_Z	0.04	26.21	8.01	8.44	warning!
3RD	3RD_X	4560.35	0.22	3RD_Z	0.07	15.03	8.28	8.44	warning!
4TH	4TH_X	7232.41	0.14	4TH_Z	0.10	10.29	8.63	8.44	ok
5TH	5TH_X	10388.11	0.10	5TH_Z	0.13	7.74	8.97	8.44	ok
6TH	6TH_X	13961.48	0.07	6TH_Z	0.16	6.16	9.27	8.44	ok
7TH	7TH_X	17902.83	0.06	7TH_Z	0.20	5.09	9.55	8.44	ok
8TH	8TH_X	22183.46	0.05	8TH_Z	0.23	4.32	9.79	8.44	ok
9TH	9TH_X	26801.61	0.04	9TH_Z	0.27	3.74	10.01	8.44	ok
10TH	10TH_X	31785.89	0.03	10TH_Z	0.30	3.28	10.21	8.44	ok
11TH	11TH_X	37268.33	0.03	11TH_Z	0.34	2.90	10.40	8.44	ok
12TH	12TH_X	43334.96	0.02	12TH_Z	0.39	2.58	10.58	8.44	ok
13TH	13TH_X	50263.30	0.02	13TH_Z	0.43	2.31	10.77	8.44	ok
RL	RL_X	58983.02	0.02	RL_Z	0.49	2.03	10.95	8.44	ok
RT	RT_X	68487.80	0.01	RT_Z	0.64	1.57	10.38	8.44	ok

Table 5-23 Summary of torsional radius (r_x)

Story	Load case	U_y(mm)	K_{fy}	Load case	R_z(rad)	K_M	r_x	l_s	$r_x>l_s$
GF	GF_Y	40.60	24.63	GF_Z	0.00	2610.97	10.30	8.44	ok
1ST	1^{ST}_Y	394.26	2.54	1^{ST}_Z	0.01	106.89	6.49	8.44	warning!
2ND	2^{ND}_Y	1651.32	0.61	2^{ND}_Z	0.04	26.21	6.58	8.44	warning!
3RD	3^{RD}_Y	3218.70	0.31	3^{RD}_Z	0.07	15.03	6.96	8.44	warning!
4TH	4^{TH}_Y	5248.82	0.19	4^{TH}_Z	0.10	10.29	7.35	8.44	warning!
5TH	5^{TH}_Y	7688.37	0.13	5^{TH}_Z	0.13	7.74	7.71	8.44	warning!
6TH	6^{TH}_Y	10489.07	0.10	6^{TH}_Z	0.16	6.16	8.04	8.44	warning!
7TH	7^{TH}_Y	13616.08	0.07	7^{TH}_Z	0.20	5.09	8.32	8.44	warning!
8TH	8^{TH}_Y	17052.29	0.06	8^{TH}_Z	0.23	4.32	8.58	8.44	ok
9TH	9^{TH}_Y	20803.14	0.05	9^{TH}_Z	0.27	3.74	8.82	8.44	ok
10TH	10^{TH}_Y	24915.92	0.04	10^{TH}_Z	0.30	3.28	9.04	8.44	ok
11TH	11^{TH}_Y	29399.01	0.03	11^{TH}_Z	0.34	2.90	9.23	8.44	ok
12TH	12^{TH}_Y	34351.67	0.03	12^{TH}_Z	0.39	2.58	9.42	8.44	ok
13TH	13^{TH}_Y	39964.28	0.03	13^{TH}_Z	0.43	2.31	9.61	8.44	ok
RL	RL_Y	47026.56	0.02	RL_Z	0.49	2.03	9.78	8.44	ok
RT	RT_Y	54390.00	0.02	RT_Z	0.64	1.57	9.25	8.44	ok

The distance between the center of mass and center of rigidity of each floor has to be less than thirty percent of the torsional radius. Each floor is checked for this requirement of the code and results are summarized in **Table 5-24** and **Table 5-25**.

Table 5-24 Summary of Eccentricity-X

Story	Diaphragm	Center of mass (X)	Center of stiffness (X)	Eccentricity-X (m)	r_x(m)	$Ecc_x<0.3r_x$
GF	GF	9.73	11.29	1.5658	10.30	ok
1ST	1ST	8.24	7.05	1.1870	6.49	ok
2ND	2ND	9.19	7.04	2.1518	6.58	warning!
3RD	3RD	9.23	7.09	2.1489	6.96	warning!
4TH	4TH	9.23	7.16	2.0746	7.35	ok
5TH	5TH	9.23	7.25	1.9894	7.71	ok
6TH	6TH	9.23	7.34	1.8985	8.04	ok
7TH	7TH	9.23	7.43	1.8038	8.32	ok
8TH	8TH	9.23	7.53	1.7058	8.58	ok
9TH	9TH	9.23	7.63	1.6029	8.82	ok
10TH	10TH	9.07	7.74	1.3314	9.04	ok
11TH	11TH	9.08	7.86	1.2235	9.23	ok
12TH	12TH	9.08	7.98	1.1020	9.42	ok
13TH	13TH	8.99	8.11	0.8871	9.61	ok
RL	RL	9.09	8.24	0.8507	9.78	ok
RT	RT	8.85	8.46	0.3849	9.25	ok

Table 5-25 Summary of Eccentricity-Y

Story	Diaphragm	Center of mass (Y)	Center of stiffness (Y)	Eccentricity-Y (m)	r_y(m)	$Ecc_y<0.3r_y$
GF	GF	12.11	16.93	4.82	12.00	warning!
1^{ST}	1^{ST}	11.61	11.12	0.49	8.31	ok
2^{ND}	2^{ND}	9.72	10.68	0.95	8.01	ok
3^{RD}	3^{RD}	9.81	10.57	0.76	8.28	ok
4^{TH}	4^{TH}	9.81	10.53	0.72	8.63	ok
5^{TH}	5^{TH}	9.81	10.52	0.71	8.97	ok
6^{TH}	6^{TH}	9.81	10.53	0.72	9.27	ok
7^{TH}	7^{TH}	9.81	10.54	0.73	9.55	ok
8^{TH}	8^{TH}	9.81	10.55	0.74	9.79	ok
9^{TH}	9^{TH}	9.81	10.57	0.76	10.01	ok
10^{TH}	10^{TH}	9.99	10.60	0.61	10.21	ok
11^{TH}	11^{TH}	9.91	10.66	0.75	10.40	ok
12^{TH}	12^{TH}	9.91	10.73	0.82	10.58	ok
13^{TH}	13^{TH}	9.89	10.82	0.93	10.77	ok
RL	RL	9.97	10.93	0.97	10.95	ok
RT	RT	14.14	10.90	3.24	10.38	warning!

5.1.1.3.2 Program results for torsional rigidity

The program only asks the user for the radius of gyration. The radius of gyration is calculated on previous sections and it amounts to 8.444m. As the building model is yet to be designed for torsional rigidity, the first option is chosen as the model status. **Figure 5-10** shows input data fed into the program.

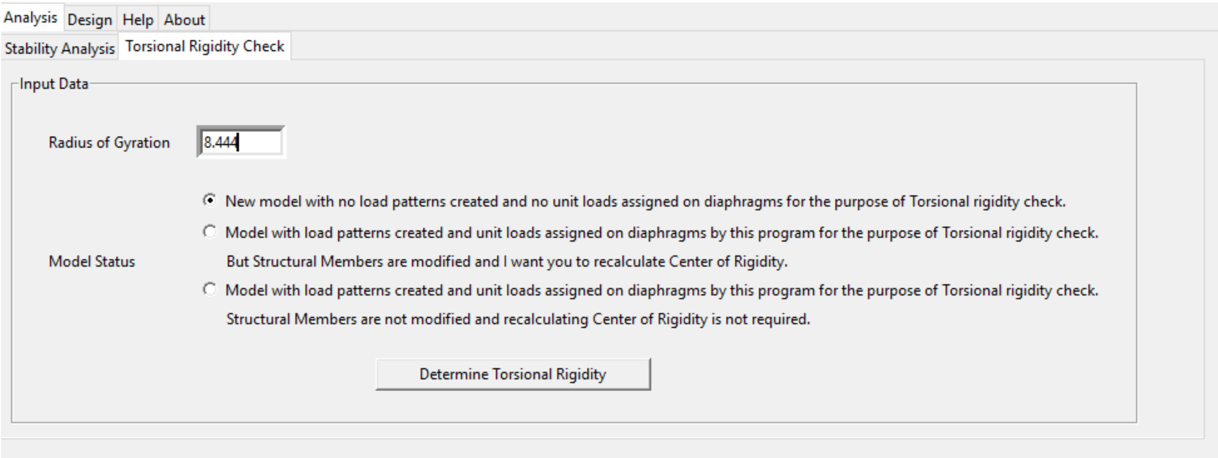


Figure 5-10 Input data for torsional radius calculation

By interacting to the open instance of ETABS model through the API, the program analysed the model for torsional rigidity. Required input data from the user is also made available to the program through the developed user interface. Analysis results from the program are shown in **Figure 5-11** and **Figure 5-12**.

X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	ls	Ecc_X<0.3rx	rx>ls
GF	9.728	11.2938	-1.5657999999999994	10.29601053312	8.444	ok	ok
1ST	8.2393	7.0523	1.1870000000000003	6.49189767599	8.444	ok	warning!
2ND	9.1876	7.0358	2.1517999999999997	6.57879128994	8.444	warning!	warning!
3RD	9.2347	7.0858	2.1489000000000003	6.95633766371	8.444	warning!	warning!
4TH	9.2347	7.1601	2.0746	7.35007277891	8.444	ok	warning!
5TH	9.2347	7.2453	1.9893999999999998	7.71312346882	8.444	ok	warning!
6TH	9.2347	7.3362	1.8985000000000003	8.03688170296	8.444	ok	warning!
7TH	9.2347	7.4309	1.8037999999999998	8.32456051445	8.444	ok	warning!
8TH	9.2347	7.5289	1.7058	8.58285480449	8.444	ok	ok
9TH	9.2347	7.6318	1.6029	8.81893993098	8.444	ok	ok
10TH	9.0737	7.7423	1.3314000000000004	9.03875201255	8.444	ok	ok
11TH	9.0819	7.8584	1.2234999999999996	9.23485233466	8.444	ok	ok
12TH	9.0819	7.9799	1.1019999999999994	9.42085588009	8.444	ok	ok
13TH	8.9941	8.107	0.8871000000000002	9.60617402479	8.444	ok	ok
RL	9.0949	8.2442	0.8507000000000016	9.78158892165	8.444	ok	ok
RT	8.8497	8.4648	0.3849	9.24860786629	8.444	ok	ok

Figure 5-11 Torsion analysis results from the program (X-direction)

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	Is	Ecc_Y<0.3ry	ry>Is
GF	12.1086	16.9302	-4.8216	11.99706230359	8.444	warning!	ok
1ST	11.6119	11.1181	0.49380000000000024	8.31160252325	8.444	ok	warning!
2ND	9.7246	10.6774	-0.9527999999999999	8.01402620595	8.444	ok	warning!
3RD	9.8116	10.5701	-0.7584999999999997	8.28017069817	8.444	ok	warning!
4TH	9.8116	10.534	-0.7224000000000004	8.62784244683	8.444	ok	ok
5TH	9.8116	10.5246	-0.7129999999999992	8.96564537351	8.444	ok	ok
6TH	9.8116	10.528	-0.7164000000000001	9.27224185558	8.444	ok	ok
7TH	9.8116	10.5379	-0.7263000000000002	9.54544420131	8.444	ok	ok
8TH	9.8116	10.5521	-0.740499999999999	9.78937762182	8.444	ok	ok
9TH	9.8121	10.571	-0.7589000000000006	10.0099592253	8.444	ok	ok
10TH	9.9876	10.5974	-0.6097999999999999	10.2090945179	8.444	ok	ok
11TH	9.9072	10.6553	-0.7481000000000009	10.3976108369	8.444	ok	ok
12TH	9.9087	10.7284	-0.819700000000001	10.5812178061	8.444	ok	ok
13TH	9.8927	10.8187	-0.9260000000000002	10.7730806075	8.444	ok	ok
RL	9.9662	10.9325	-0.9662999999999986	10.9547204570	8.444	ok	ok
RT	14.1405	10.9024	3.2380999999999993	10.3782341424	8.444	warning!	ok

Figure 5-12 Torsion analysis results from the program (Y-direction)

5.1.1.3.3 Torsion analysis results comparison

As both the developed program and the executed manual calculation followed standard procedures recommended by the building design code, deviation between output results is not expected. Summary of comparison between manual analysis and program analysis is shown on **Table 5-26** and **Table 5-27**.

Table 5-26 Comparison for Eccentricity results

Story	Diaphragm	Manual analysis		Program analysis		% difference	
		Ecc-X (m)	Ecc-Y (m)	Ecc-X (m)	Ecc-Y (m)	Ecc-X	Ecc-Y
GF	GF	1.57	4.82	1.57	4.82	0.00	0.00
1^{ST}	1^{ST}	1.19	0.49	1.19	0.49	0.00	0.00
2^{ND}	2^{ND}	2.15	0.95	2.15	0.95	0.00	0.00
3^{RD}	3^{RD}	2.15	0.76	2.15	0.76	0.00	0.00
4^{TH}	4^{TH}	2.07	0.72	2.07	0.72	0.00	0.00
5^{TH}	5^{TH}	1.99	0.71	1.99	0.71	0.00	0.00
6^{TH}	6^{TH}	1.90	0.72	1.90	0.72	0.00	0.00
7^{TH}	7^{TH}	1.80	0.73	1.80	0.73	0.00	0.00
8^{TH}	8^{TH}	1.71	0.74	1.71	0.74	0.00	0.00
9^{TH}	9^{TH}	1.60	0.76	1.60	0.76	0.00	0.00
10^{TH}	10^{TH}	1.33	0.61	1.33	0.61	0.00	0.00
11^{TH}	11^{TH}	1.22	0.75	1.22	0.75	0.00	0.00
12^{TH}	12^{TH}	1.10	0.82	1.10	0.82	0.00	0.00
13^{TH}	13^{TH}	0.89	0.93	0.89	0.93	0.00	0.00
RL	RL	0.85	0.97	0.85	0.97	0.00	0.00
RT	RT	0.38	3.24	0.38	3.24	0.00	0.00

Table 5-27 Comparison for Torsional radius results

Story	Diaphragm	Manual analysis		Program analysis		% difference	
		r_x(m)	r_y(m)	r_x(m)	r_y(m)	r_x	r_y
GF	GF	10.30	12.00	10.30	12.00	0.00	0.00
1^{ST}	1^{ST}	6.49	8.31	6.49	8.31	0.00	0.00
2^{ND}	2^{ND}	6.58	8.01	6.58	8.01	0.00	0.00
3^{RD}	3^{RD}	6.96	8.28	6.96	8.28	0.00	0.00
4^{TH}	4^{TH}	7.35	8.63	7.35	8.63	0.00	0.00
5^{TH}	5^{TH}	7.71	8.97	7.71	8.97	0.00	0.00
6^{TH}	6^{TH}	8.04	9.27	8.04	9.27	0.00	0.00
7^{TH}	7^{TH}	8.32	9.55	8.32	9.55	0.00	0.00
8^{TH}	8^{TH}	8.58	9.79	8.58	9.79	0.00	0.00
9^{TH}	9^{TH}	8.82	10.01	8.82	10.01	0.00	0.00
10^{TH}	10^{TH}	9.04	10.21	9.04	10.21	0.00	0.00
11^{TH}	11^{TH}	9.23	10.40	9.23	10.40	0.00	0.00
12^{TH}	12^{TH}	9.42	10.58	9.42	10.58	0.00	0.00
13^{TH}	13^{TH}	9.61	10.77	9.61	10.77	0.00	0.00
RL	RL	9.78	10.95	9.78	10.95	0.00	0.00
RT	RT	9.25	10.38	9.25	10.38	0.00	0.00

5.1.2 Design

The focus of this subsection is on verify the program's ability to efficiently design buildings for lateral stability and torsional rigidity. The goal is to demonstrate that the program can achieve the desired design outcomes with fewer iterations compared to traditional hand analysis methods. To provide a comprehensive analysis and design, a specific floor (3rd floor) was selected as the basis of design, as it exhibited inadequacies when evaluated against various parameters. This section will delve into the problem identification and problem-solving processes, examining how the program addresses these challenges to optimize the design.

5.1.2.1 Problem identification

In the problem identification phase, several parameters are fed into the program to guide the analysis and detection of structural issues. Firstly, the program takes into account the user's preferences regarding the acceptable range of values for the drift sensitivity coefficient. This allows the user to define their desired level of sensitivity the building is to have against second order effects. Additionally, the user have to specify the target floor for the program to focus on, enabling the detection and resolution of structural problems specific to that floor.

To facilitate this interaction, a user-friendly interface has been developed. The interface allows the user to input their preferences and receive feedback on detected problems and suggested solutions. Through this interface, the program effectively communicates with the user, enabling a collaborative design process and ensuring that the final solution aligns with the user's requirements. **Figure 5-13** shows the graphical user interface window and parameters fed into it while designing the example model.

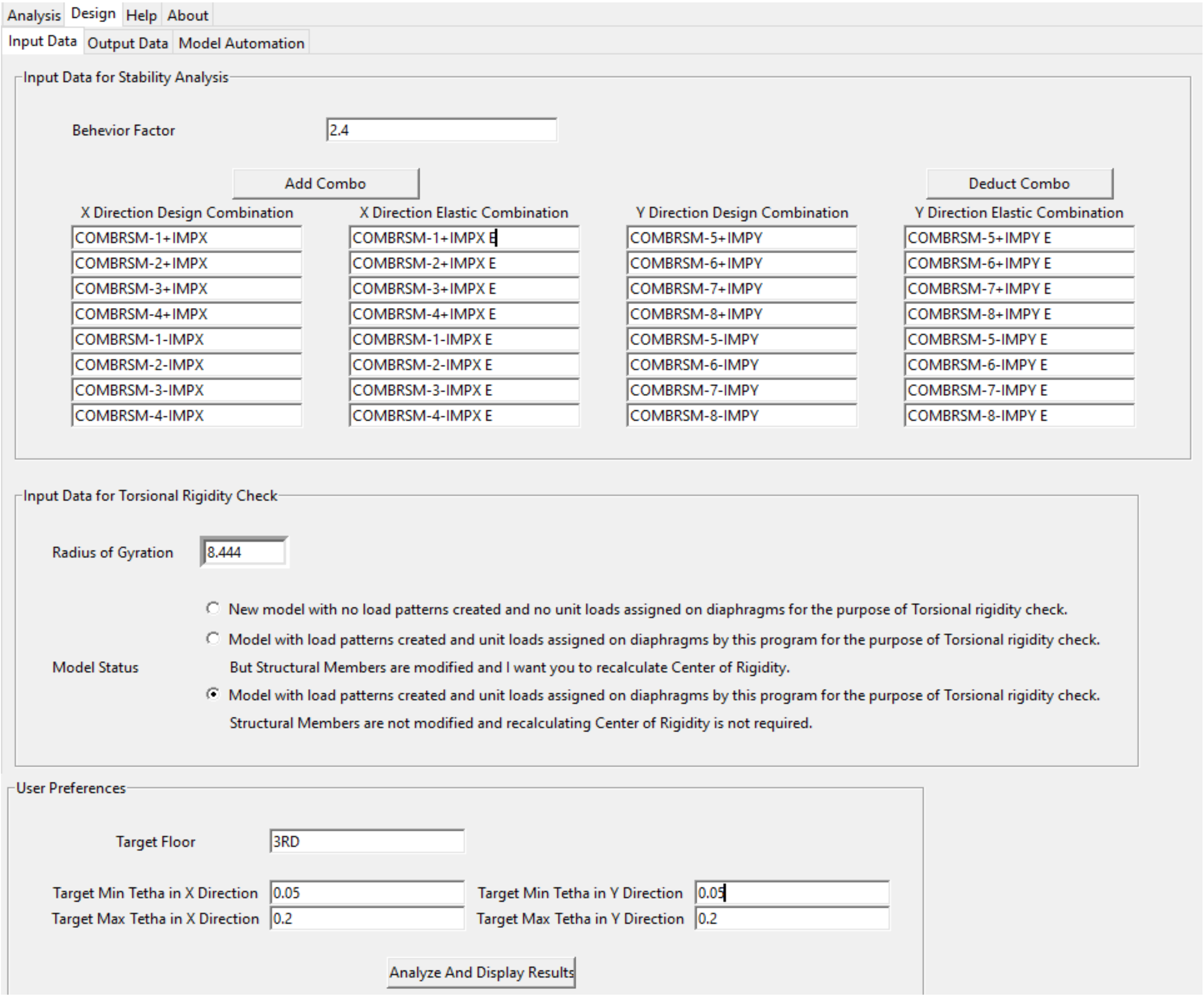


Figure 5-13 Input data for the design of the building

The program's problem detection capacity is a key aspect of its functionality. It conducts a comprehensive assessment of six parameters that express both stability and torsional rigidity. These parameters are checked against the allowable limits specified in the design code. This analysis provides valuable insights into the structural shortcomings of the target floor and serves as the foundation for generating appropriate design solutions. Structural problems of the building under consideration are identified by the program and presented in **Figure 5-14**.

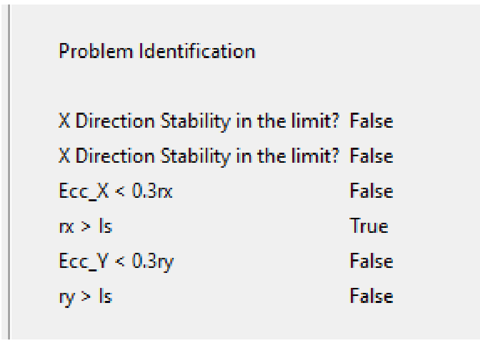


Figure 5-14 Identified problems

5.1.2.2 Problem solving

The program utilizes the problems identified during the analysis phase as the basis for suggesting structural solutions. By taking into account the specific issues detected in the target floor, the program aims to address and rectify these problems effectively. These suggested solutions serve as valuable guidance for structural engineers and designers in improving seismic performance of the building.

Moving forward, the problem-solving capacity of the program demonstrates its versatility and adaptability. The program has the capability to handle multiple combinations of building problems, with a potential of up to 64 types of problem combinations that can be detected in a building model. Each problem within this extensive range exhibits its own variability, presenting unique challenges and considerations. For instance, if the building's drift sensitivity coefficient value falls outside the user's specified preference range, the program determines the specific side of the range towards where the value deviates. Moreover, an assessment of the parameters in relation to each other is performed to determine the severity of each problem. To address this complex landscape, the program encompasses nearly two thousand predefined solutions tailored to the specific problem at hand.

During the implementation of the program's suggested solutions, iterations are involved to identify the most effective course of action. Four possible solution options are generated by the program, out of which the first and the third are attempted.

Suggested Solutions

Solution_1	Add_Y_Direction_Wall_In_The_Right_And_X_Direction_Wall_In_The_Bottom_Side_Of_The_Building
Solution_2	Thicken_Y_Direction_Wall_In_The_Right_And_X_Direction_Wall_In_The_Bottom_Side_Of_The_Building
Solution_3	Add_Y_Direction_Wall_In_The_Right_And_X_Direction_Wall_In_The_Top_And_Bottom_Side_Of_The_Building
Solution_4	Thicken_Y_Direction_Wall_In_The_Right_And_X_Direction_Wall_In_The_Top_And_Bottom_Side_Of_The_Building

Figure 5-15 Program generated solutions

Option 1 shows a significant enhancement across all parameters, yet it falls short of achieving the desired outcomes. Conversely, option 2 proves to be a transformative solution, successfully resolving all identified issues simultaneously. The results of the torsional rigidity check and stability analysis after applying suggestion option 3 are reported on figures **Figure 5-16** to **Figure 5-21**.

X Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	X	Max	COMBRSM-1+IMPX	0.006893955209452239	Good
RL	X	Max	COMBRSM-1+IMPX	0.01694075693287856	Good
13TH	X	Max	COMBRSM-1+IMPX	0.027959164508787188	Good
12TH	X	Max	COMBRSM-1+IMPX	0.03777560015912378	Good
11TH	X	Max	COMBRSM-1+IMPX	0.04718347850021997	Good
10TH	X	Max	COMBRSM-1+IMPX	0.05060314248351549	Good
9TH	X	Max	COMBRSM-1+IMPX	0.057439648855029064	Good
8TH	X	Max	COMBRSM-1+IMPX	0.0627894266375962	Good
7TH	X	Max	COMBRSM-1+IMPX	0.06639027240932568	Good
6TH	X	Max	COMBRSM-1+IMPX	0.06755110365961275	Good
5TH	X	Max	COMBRSM-1+IMPX	0.06573669061387238	Good
4TH	X	Max	COMBRSM-1+IMPX	0.06132204203717333	Good
3RD	X	Max	COMBRSM-1+IMPX	0.054793778204515226	Good
2ND	X	Max	COMBRSM-1+IMPX	0.045078424676739184	Good
1ST	X	Max	COMBRSM-1+IMPX	0.03640359245129274	Good
GF	X	Max	COMBRSM-1+IMPX	0.023689466436169877	Good

Figure 5-16 Stability design results from the program (X-Max)

X Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	X	Min	COMBRSM-1-IMPX	0.005768575712418052	Good
RL	X	Min	COMBRSM-1-IMPX	0.013998637916548923	Good
13TH	X	Min	COMBRSM-1-IMPX	0.023351847322945176	Good
12TH	X	Min	COMBRSM-1-IMPX	0.030984528237305388	Good
11TH	X	Min	COMBRSM-1-IMPX	0.036639914910519794	Good
10TH	X	Min	COMBRSM-1-IMPX	0.0369120190904033	Good
9TH	X	Min	COMBRSM-1-IMPX	0.043617788130911404	Good
8TH	X	Min	COMBRSM-1-IMPX	0.04945397285935711	Good
7TH	X	Min	COMBRSM-1-IMPX	0.05392908270185016	Good
6TH	X	Min	COMBRSM-1-IMPX	0.0562653075034315	Good
5TH	X	Min	COMBRSM-1-IMPX	0.05574531698939715	Good
4TH	X	Min	COMBRSM-1-IMPX	0.05240196063705568	Good
3RD	X	Min	COMBRSM-1-IMPX	0.04716817074774411	Good
2ND	X	Min	COMBRSM-1-IMPX	0.040048804652424705	Good
1ST	X	Min	COMBRSM-1-IMPX	0.027494383584882428	Good
GF	X	Min	COMBRSM-1-IMPX	0.008279798524562215	Good

Figure 5-17 Stability design results from the program (X-Min)

Y Direction (Max)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	Y	Max	COMBRSM-5+IMPY	0.013106804387715481	Good
RL	Y	Max	COMBRSM-5+IMPY	0.025844728574693047	Good
13TH	Y	Max	COMBRSM-5+IMPY	0.04073470882159516	Good
12TH	Y	Max	COMBRSM-5+IMPY	0.05599669597003005	Good
11TH	Y	Max	COMBRSM-5+IMPY	0.0721308378611566	Good
10TH	Y	Max	COMBRSM-5+IMPY	0.08640194001156977	Good
9TH	Y	Max	COMBRSM-5+IMPY	0.10454464221485772	P-Delta required
8TH	Y	Max	COMBRSM-5+IMPY	0.12061640267014777	P-Delta required
7TH	Y	Max	COMBRSM-5+IMPY	0.1325490232425798	P-Delta required
6TH	Y	Max	COMBRSM-5+IMPY	0.13922376865943198	P-Delta required
5TH	Y	Max	COMBRSM-5+IMPY	0.13965742852248492	P-Delta required
4TH	Y	Max	COMBRSM-5+IMPY	0.13396615469120482	P-Delta required
3RD	Y	Max	COMBRSM-5+IMPY	0.12272847955998076	P-Delta required
2ND	Y	Max	COMBRSM-5+IMPY	0.10129739467033386	P-Delta required
1ST	Y	Max	COMBRSM-5+IMPY	0.06700873313343955	Good
GF	Y	Max	COMBRSM-5+IMPY	0.01317760069547	Good

Figure 5-18 Stability design results from the program (Y-Max)

Y Direction (Min)

Storey	Direction	Step Type	Combination	Tetha	Status
RT	Y	Min	COMBRSM-5-IMPY	0.015965895644588373	Good
RL	Y	Min	COMBRSM-5-IMPY	0.03190355937155319	Good
13TH	Y	Min	COMBRSM-5-IMPY	0.04969927298336461	Good
12TH	Y	Min	COMBRSM-5-IMPY	0.06778478163448315	Good
11TH	Y	Min	COMBRSM-5-IMPY	0.08767068457192122	Good
10TH	Y	Min	COMBRSM-5-IMPY	0.1071558663921841	P-Delta required
9TH	Y	Min	COMBRSM-5-IMPY	0.127343515080424	P-Delta required
8TH	Y	Min	COMBRSM-5-IMPY	0.14410886152422384	P-Delta required
7TH	Y	Min	COMBRSM-5-IMPY	0.15612765514346288	P-Delta required
6TH	Y	Min	COMBRSM-5-IMPY	0.1616838359938238	P-Delta required
5TH	Y	Min	COMBRSM-5-IMPY	0.15984505695591156	P-Delta required
4TH	Y	Min	COMBRSM-5-IMPY	0.1508329065552452	P-Delta required
3RD	Y	Min	COMBRSM-5-IMPY	0.13489395119829947	P-Delta required
2ND	Y	Min	COMBRSM-5-IMPY	0.10812922569660112	P-Delta required
1ST	Y	Min	COMBRSM-5-IMPY	0.06985598371924878	Good
GF	Y	Min	COMBRSM-5-IMPY	0.011624198493965092	Good

Figure 5-19 Stability design results from the program (Y-Min)

X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	Is	Ecc_X<0.3rx	rx>Is
GF	9.8929	11.2518	-1.3589000000000002	10.58086963627	8.444	ok	ok
1ST	8.2293	11.4348	-3.205499999999999	12.31340318349	8.444	ok	ok
2ND	9.1222	12.2722	-3.1500000000000004	12.56036855321	8.444	ok	ok
3RD	9.1738	12.35	-3.1761999999999997	12.59486421405	8.444	ok	ok
4TH	9.1738	12.2564	-3.0825999999999993	12.59464546869	8.444	ok	ok
5TH	9.1738	12.0945	-2.9207	12.58428793016	8.444	ok	ok
6TH	9.1738	11.9048	-2.731	12.56613601915	8.444	ok	ok
7TH	9.1738	11.7072	-2.5334000000000003	12.53969396268	8.444	ok	ok
8TH	9.1738	11.5136	-2.3398000000000003	12.50177435656	8.444	ok	ok
9TH	9.1737	11.3304	-2.156699999999999	12.44376091242	8.444	ok	ok
10TH	9.0445	11.1698	-2.125300000000001	12.36341129041	8.444	ok	ok
11TH	9.0819	11.0498	-1.9679000000000002	12.31871488288	8.444	ok	ok
12TH	9.0819	10.8283	-1.7464000000000013	12.16488199940	8.444	ok	ok
13TH	8.9941	10.607	-1.6128999999999998	12.00715153669	8.444	ok	ok
RL	9.0949	10.3804	-1.285499999999999	11.82368495238	8.444	ok	ok
RT	8.8497	9.9628	-1.1130999999999993	10.31652378565	8.444	ok	ok

Figure 5-20 Torsional rigidity design results from the program (X-Direction)

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	ls	Ecc_Y<0.3ry	ry>ls
GF	12.6886	16.0367	-3.3481000000000005	12.01035334911	8.444	ok	ok
1ST	11.6692	11.4562	0.2129999999999992	11.70832274190	8.444	ok	ok
2ND	9.6156	10.5021	-0.8864999999999998	11.71800049648	8.444	ok	ok
3RD	9.7097	10.169	-0.4593000000000007	11.58333532768	8.444	ok	ok
4TH	9.7097	9.9796	-0.2698999999999998	11.54460580249	8.444	ok	ok
5TH	9.7097	9.8683	-0.15859999999999985	11.53988435152	8.444	ok	ok
6TH	9.7097	9.8071	-0.09740000000000038	11.55011684563	8.444	ok	ok
7TH	9.7097	9.7797	-0.07000000000000028	11.56476998717	8.444	ok	ok
8TH	9.7097	9.775	-0.06530000000000058	11.57604303290	8.444	ok	ok
9TH	9.7102	9.7834	-0.07319999999999993	11.57616753347	8.444	ok	ok
10TH	9.9314	9.7979	0.1334999999999973	11.53695270875	8.444	ok	ok
11TH	9.9072	9.89	0.01719999999998994	11.56360507044	8.444	ok	ok
12TH	9.9087	10.0322	-0.12349999999999994	11.50470297764	8.444	ok	ok
13TH	9.8927	10.2042	-0.31150000000000055	11.47592507767	8.444	ok	ok
RL	9.9662	10.4123	-0.4460999999999995	11.43617440702	8.444	ok	ok
RT	14.1405	10.4651	3.6754	9.784647370706	8.444	warning!	ok

Figure 5-21 Torsional rigidity design results from the program (Y-Direction)

5.2 Verification based on Eurocode 8: Worked Example

As a support to the implementation, harmonization and further development of the Eurocodes, the European Commission Joint Research Centre published a book by the title Eurocode 8: Seismic Design of Buildings: Worked examples. [34] The publications main intent is to assist designers working on structural design of buildings located in seismic regions. In order to facilitate the realization objectives of the publication, a sample 3D building model is created and used for explaining different design aspects of structural design. Determination of torsional rigidity of building structures is one of the many structural design aspects covered by the book. The building model is reproduced and analyzed by the developed program for torsional rigidity. Results of the design example are then compared with the results produced by the program to validate the proper functioning of the software.

5.2.1 Modelling

The building model is expressed through the use of floor plans, elevation diagrams and verbal expressions. Through the use of information stated above, the building model is reproduced on ETABS analysis software. The three-dimensional structural model developed on ETABS software is shown on **Figure 5-22**. To reproduce the results presented in the design example, it is mandatory to recreate the building model accurately. Most of the parameters required for the modelling task are available. Only some structural parameters required for modelling purpose are not made available, but that is not expected to change the final result significantly.

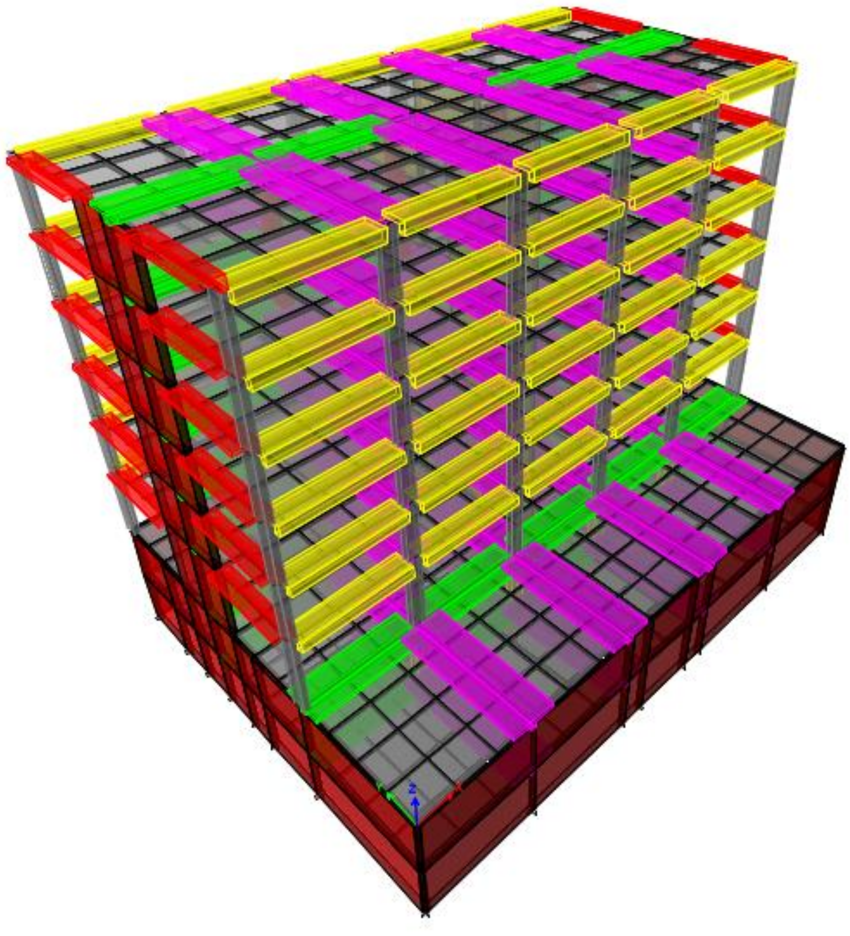


Figure 5-22 3D Model of the example building.

5.2.2 Program analysis

The only parameter the program requires for torsional rigidity check of a given building model is the radius of gyration. The radius of gyration of the floor mass in plan is calculated 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. For a rectangular floor plan with uniformly distributed load, the radius of gyration can be calculated as based on equation 5-7:

For the building under consideration, radius of gyration for the typical floor plans is calculated as follows.

Ground and Basement floors:

$$l_s = \sqrt{\frac{30^2 + 21^2}{12}} = 10.57m$$

Typical floors above the ground level:

$$l_s = \sqrt{\frac{30^2 + 14^2}{12}} = 9.56m$$

The user is also expected to inform the program what the status of the model to be analyzed is. Three options for the model status are presented to the user. To check for the proper functioning of the program for all available cases, analysis using the program is performed for all model types.

5.2.2.1 Model Type 1

From the three options available for selection of the type of model, new model with no load patterns created and no loads assigned on diaphragms for the purpose of Torsional rigidity check is selected. After receiving this information, the program went on to perform tasks of calculating center of rigidity, creating point objects on the centers of rigidity of each floor, assigning lateral loads and moments on the created joints and analyzing the structure for the results of the applied loads. The results are then processed to check the torsional rigidity of the building model. Input data fed into the program and output results of the program are shown on **Figure 5-23** to **Figure 5-25**.

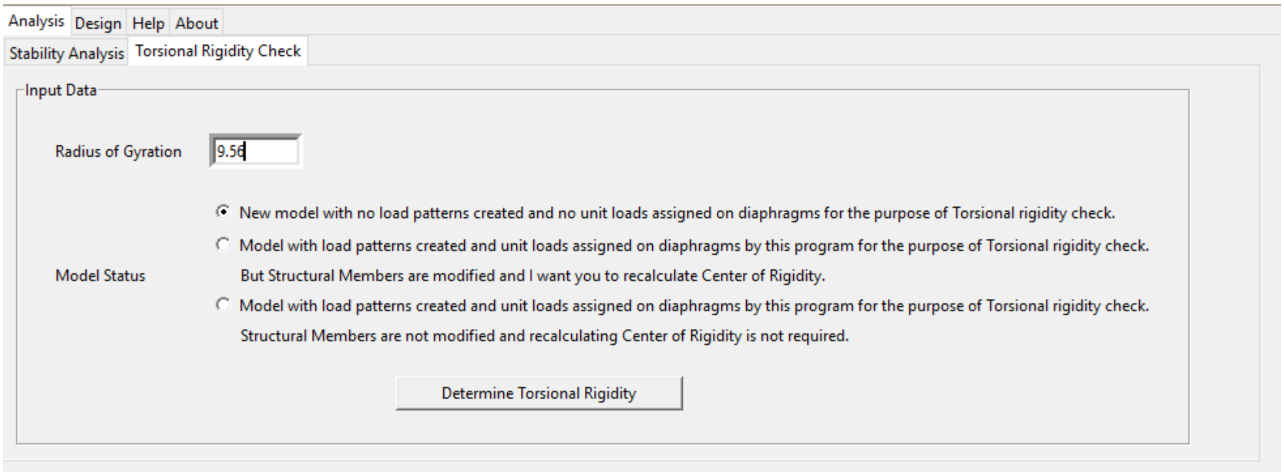


Figure 5-23 Input data for the case of Model Type 1

X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	Is	Ecc_X<0.3rx	rx>Is
IEVEL-1	15	15	0.0	18.58521607112	9.56	ok	ok
LEVEL 0	15	15	0.0	19.96081066149	9.56	ok	ok
LEVEL 1	15	15	0.0	12.67095136901	9.56	ok	ok
LEVEL 2	15	15	0.0	12.25857272059	9.56	ok	ok
LEVEL 3	15	15	0.0	12.24398456331	9.56	ok	ok
LEVEL 4	15	15	0.0	12.33271206225	9.56	ok	ok
LEVEL 5	15	15	0.0	12.43848427440	9.56	ok	ok
ROOF	15	15	0.0	12.51765005947	9.56	ok	ok

Figure 5-24 Y-direction results for Model type 1

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	Is	Ecc_Y<0.3ry	ry>Is
IEVEL-1	10.6132	10.4825	0.13070000000000093	16.22122699206	9.56	ok	ok
LEVEL 0	10.8213	10.4856	0.335700000000001	16.77880513882	9.56	ok	ok
LEVEL 1	13.9675	11.2969	2.6705999999999985	20.45008521632	9.56	ok	ok
LEVEL 2	13.9712	11.6096	2.3615999999999993	18.58409273101	9.56	ok	ok
LEVEL 3	13.9712	11.9308	2.0404	17.46662386052	9.56	ok	ok
LEVEL 4	13.9712	12.2257	1.7454999999999998	16.76526351814	9.56	ok	ok
LEVEL 5	13.9711	12.4708	1.5002999999999993	16.28221290511	9.56	ok	ok
ROOF	13.984	12.6351	1.3489000000000004	15.88335631745	9.56	ok	ok

Figure 5-25 Y-direction results for Model type 1

5.2.2.2 Model Type 2

From the three options available for selection of the type of model, "Model with load patterns created and loads assigned on diaphragms by this program for the purpose of Torsional rigidity check. But Structural Members are modified and Center of Rigidity of building floors shall be recalculated" is selected. After receiving this information, the program went on to perform tasks of disconnecting diaphragm of previously created joint objects, deleting previously created point object, calculating center of rigidity, creating point objects on the centers of rigidity of each floor, assigning lateral loads and moments on the created joints and analyzing the structure for the results of the applied loads.

The results are then processed to check the torsional rigidity of the building model. Input data fed into the program and output results of the program are shown on **Figure 5-26** to **Figure 5-28**.

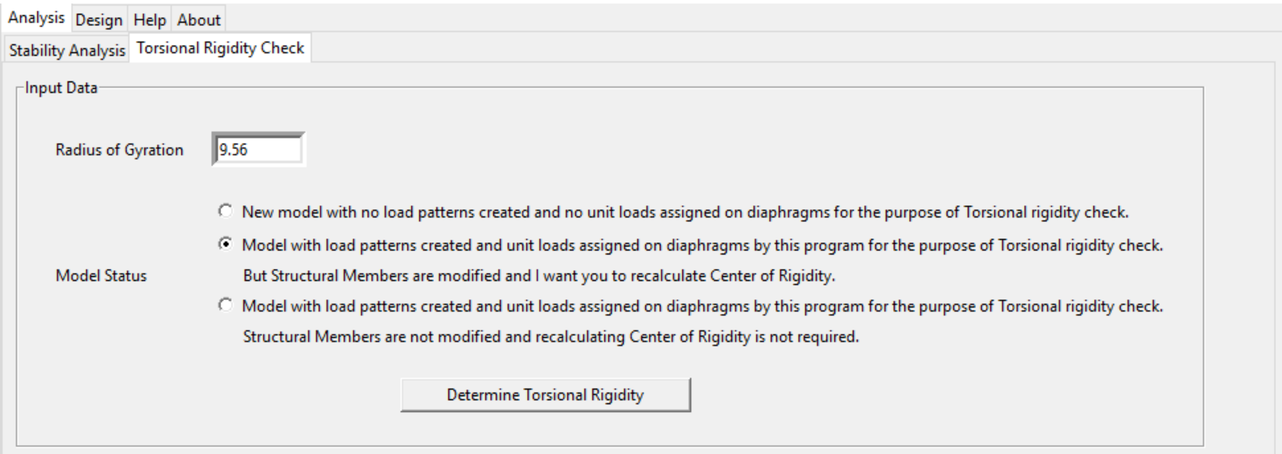


Figure 5-26 Input data for the case of Model Type 2

X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	ls	Ecc_X<0.3rx	rx>ls
lEVEL-1	15	15	0.0	18.58521607112	9.56	ok	ok
LEVEL 0	15	15	0.0	19.96081066149	9.56	ok	ok
LEVEL 1	15	15	0.0	12.67095136901	9.56	ok	ok
LEVEL 2	15	15	0.0	12.25857272059	9.56	ok	ok
LEVEL 3	15	15	0.0	12.24398456331	9.56	ok	ok
LEVEL 4	15	15	0.0	12.33271206225	9.56	ok	ok
LEVEL 5	15	15	0.0	12.43848427440	9.56	ok	ok
ROOF	15	15	0.0	12.51765005947	9.56	ok	ok

Figure 5-27 X-direction results for Model type 2

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	ls	Ecc_Y<0.3ry	ry>ls
lEVEL-1	10.6132	10.4825	0.13070000000000093	16.22122699206	9.56	ok	ok
LEVEL 0	10.8213	10.4856	0.335700000000001	16.77880513882	9.56	ok	ok
LEVEL 1	13.9675	11.2969	2.6705999999999985	20.45008521632	9.56	ok	ok
LEVEL 2	13.9712	11.6096	2.3615999999999993	18.58409273101	9.56	ok	ok
LEVEL 3	13.9712	11.9308	2.0404	17.46662386052	9.56	ok	ok
LEVEL 4	13.9712	12.2257	1.7454999999999998	16.76526351814	9.56	ok	ok
LEVEL 5	13.9711	12.4708	1.5002999999999993	16.28221290511	9.56	ok	ok
ROOF	13.984	12.6351	1.3489000000000004	15.88335631745	9.56	ok	ok

Figure 5-28 Y-direction results for Model type 2

5.2.2.3 Model Type 3

From the three options available for selection of the type of model, "Model with load patterns created and loads assigned on diaphragms by this program for the purpose of Torsional rigidity check. Structural Members are not modified and recalculating Center of Rigidity is not required" is selected. After receiving this information, the program went on to perform tasks of analyzing the structure for the results of the applied loads. The results are then processed to check the torsional rigidity of the building model. Input data fed into the program and output results of the program are shown on **Figure 5-29** to **Figure 5-31**.

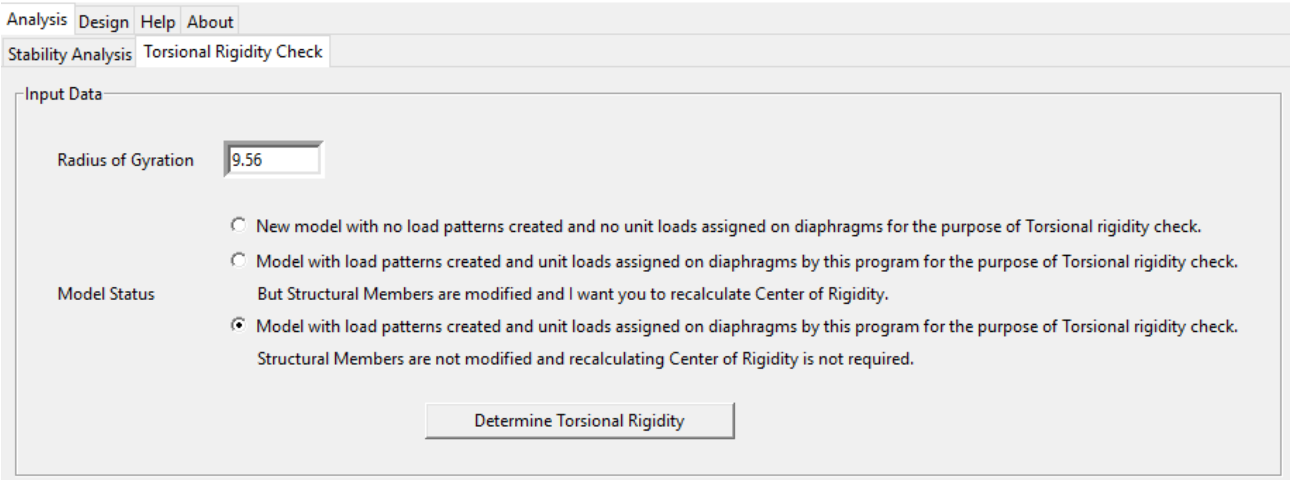
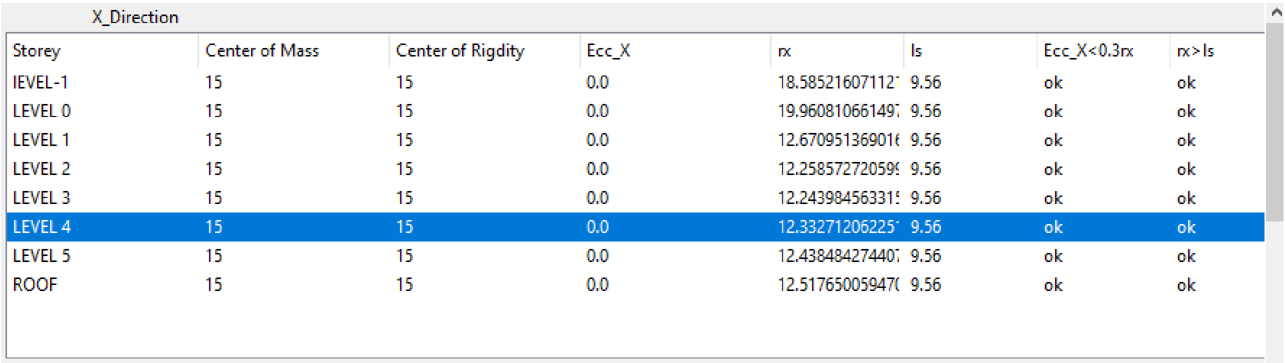


Figure 5-29 Input data for the case of Model Type 3



X_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_X	rx	Is	Ecc_X<0.3rx	rx>Is
lEVEL-1	15	15	0.0	18.58521607112	9.56	ok	ok
LEVEL 0	15	15	0.0	19.96081066149	9.56	ok	ok
LEVEL 1	15	15	0.0	12.67095136901	9.56	ok	ok
LEVEL 2	15	15	0.0	12.25857272059	9.56	ok	ok
LEVEL 3	15	15	0.0	12.24398456331	9.56	ok	ok
LEVEL 4	15	15	0.0	12.33271206225	9.56	ok	ok
LEVEL 5	15	15	0.0	12.43848427440	9.56	ok	ok
ROOF	15	15	0.0	12.51765005947	9.56	ok	ok

Figure 5-30 X-direction results for Model type 3

Y_Direction

Storey	Center of Mass	Center of Rigdity	Ecc_Y	ry	ls	Ecc_Y<0.3ry	ry>ls
lEVEL-1	10.6132	10.4825	0.13070000000000093	16.22122699206	9.56	ok	ok
LEVEL 0	10.8213	10.4856	0.335700000000001	16.77880513882	9.56	ok	ok
LEVEL 1	13.9675	11.2969	2.6705999999999985	20.45008521632	9.56	ok	ok
LEVEL 2	13.9712	11.6096	2.3615999999999993	18.58409273101	9.56	ok	ok
LEVEL 3	13.9712	11.9308	2.0404	17.46662386052	9.56	ok	ok
LEVEL 4	13.9712	12.2257	1.7454999999999998	16.76526351814	9.56	ok	ok
LEVEL 5	13.9711	12.4708	1.5002999999999993	16.28221290511	9.56	ok	ok
ROOF	13.984	12.6351	1.3489000000000004	15.88335631745	9.56	ok	ok

Figure 5-31 Y-direction results for Model type 3

From the tables shown above, it can be concluded that, output results for a single model do not vary by changing status of the model and all available options are functioning as intended. **Table 5-28** and **Table 5-29** show the summary of comparison made between model types.

Table 5-28 Summary of results (r_x)

Storey	rx (Model Type 1)	rx (Model Type 2)	rx (Model Type 3)	check
Level-1	18.58	18.58	18.58	Ok!
Level 0	19.96	19.96	19.96	Ok!
Level 1	12.67	12.67	12.67	Ok!
Level 2	12.29	12.29	12.29	Ok!
Level 3	12.24	12.24	12.24	Ok!
Level 4	12.33	12.33	12.33	Ok!
Level 5	12.44	12.44	12.44	Ok!
ROOF	12.52	12.52	12.52	Ok!

Table 5-29 Summary of results (r_y)

Storey	ry (Model Type 1)	ry (Model Type 2)	ry (Model Type 3)	Conclusion
Level-1	16.22	16.22	16.22	Ok!
Level 0	16.78	16.78	16.78	Ok!
Level 1	20.45	20.45	20.45	Ok!
Level 2	18.58	18.58	18.58	Ok!
Level 3	17.47	17.47	17.47	Ok!
Level 4	16.77	16.77	16.77	Ok!
Level 5	16.28	16.28	16.28	Ok!
ROOF	15.88	15.88	15.88	Ok!

5.3 Results and Comparison

For calculating torsional rigidity parameters r_x and r_y the design example manual used the exact same procedures and formulations as the developed program uses. For that reason, similar results are expected for a single building model. However, for reasons stated in the modelling section of this chapter, the developed model doesn't represent the model used by the writers of the example manual. **Table 5-30** and **Table 5-31** show the summary conclusions and results of both the analysis done by the program and results extracted from the example manual.

Table 5-30 Summary of comparisons (r_x)

Storey	r_x(m)			Conclusion
	Program analysis	Example manual	Difference (%)	
Level-1	18.58	18.48	0.54	Acceptable
Level 0	19.96	19.21	3.90	Acceptable
Level 1	12.67	13.21	4.09	Acceptable
Level 2	12.29	12.69	3.15	Acceptable
Level 3	12.24	12.57	2.63	Acceptable
Level 4	12.33	12.59	2.07	Acceptable
Level 5	12.44	12.66	1.74	Acceptable
ROOF	12.52	12.71	1.49	Acceptable

Table 5-31 Summary of comparisons (r_y)

Storey	r_y(m)			Conclusion
	Program analysis	Example manual	Difference (%)	
Level-1	16.22	15.91	1.95	Acceptable
Level 0	16.78	15.82	6.07	Acceptable
Level 1	20.45	21.44	4.62	Acceptable
Level 2	18.58	19.65	5.45	Acceptable
Level 3	17.47	18.38	4.95	Acceptable
Level 4	16.77	17.56	4.50	Acceptable
Level 5	16.28	16.99	4.18	Acceptable
ROOF	15.88	16.54	3.99	Acceptable

CHAPTER 6 FUZZY LOGIC-BASED BUILDING ASSESSMENT

Fuzzy logic offers a powerful approach for tackling the challenges of building problem assessment and determination of the depth of required structural modifications. The subsequent sections of this chapter will delve into the practical implementation and analysis of fuzzy logic in the assessment of a building. Each major process involved in applying fuzzy logic is explained in separate sections, accompanied by fuzzy analysis of an example model to enhance clarity and understanding.

6.1 Fuzzification

Fuzzification is the process of converting crisp input values into fuzzy values or degrees of membership in fuzzy membership functions. It involves determining the degree to which each input value belongs to the fuzzy membership functions defined for that variable. Fuzzification allows for the representation of imprecise and uncertain information, setting up the platform for the program to understand and work with the input. Fuzzification allows statements or variables to express the degree to which something was true or false through membership functions. [24]

6.1.1 Crisp inputs in to the system

In the fuzzification process, parameters representing the building's problem extent parameters are fed into the program as a crisp input. These parameters include Stability in the X-direction (Tetha_X), Stability in the Y-direction (Tetha_Y), Torsional radius in the X-direction (Tr_x), and Torsional radius in the Y-direction (Tr_y).

For the stability parameters, fuzzy sets ranging from 0.2 to 0.3 are defined, aligning with code recommendations. The fuzzy sets for the torsional radius parameters are determined based on the eccentricity data of the model, to once again comply with code recommendations.

6.1.2 Membership functions

Membership functions in fuzzy logic are mathematical representations that define the degree of membership of an element in a fuzzy set. They map the input values to fuzzy values, indicating the extent to which the input belongs to a particular category inside the fuzzy set. For the purpose of this paper, three categories inside each fuzzy set are defined and labelled as small problem, medium problem and big problem.

The shape of the membership function is chosen arbitrarily by following the advice of the expert or by statistical studies. [35] Structural engineers can be asked to define the range of numbers that represent small, medium, and big problem cases for each parameter defined as crisp input. This data can be collected through surveys or interviews. Alternatively, if such data is not available, expert knowledge and experience in the field can be utilized to define the membership functions. Opinions may vary among individuals, resulting in overlapping graphs where specific values can be partial members of multiple functions. The collected data or expert input can be plotted as scatter plot to visualize the distribution of opinions. The goal is to fit the best curve to the data points. In this case, a triangular plot is chosen as it is believed to closely represent the real distribution of opinions among structural engineers.

Membership functions are defined for both the crisp input parameters and crisp output parameters. For the purpose of this paper, four membership functions for all the crisp input parameters and one membership function for the crisp output are defined. These membership functions are shown on **Figure 6-1**.

For each input crisp values, degree of membership is quantified by reading the membership functions developed. These process of getting fuzzified variables from crisp inputs is called fuzzification. For example, the fuzzified stability value of Tetha_Y=0.2499 is [0.0013, 0.9987, 0], where variables in the bracket represent the degree to which the stability in the x direction correspond to small problem, medium problem and big problem categories. Same process of fuzzification is done for all the crisp inputs and results are summarized in **Table 6-1**.

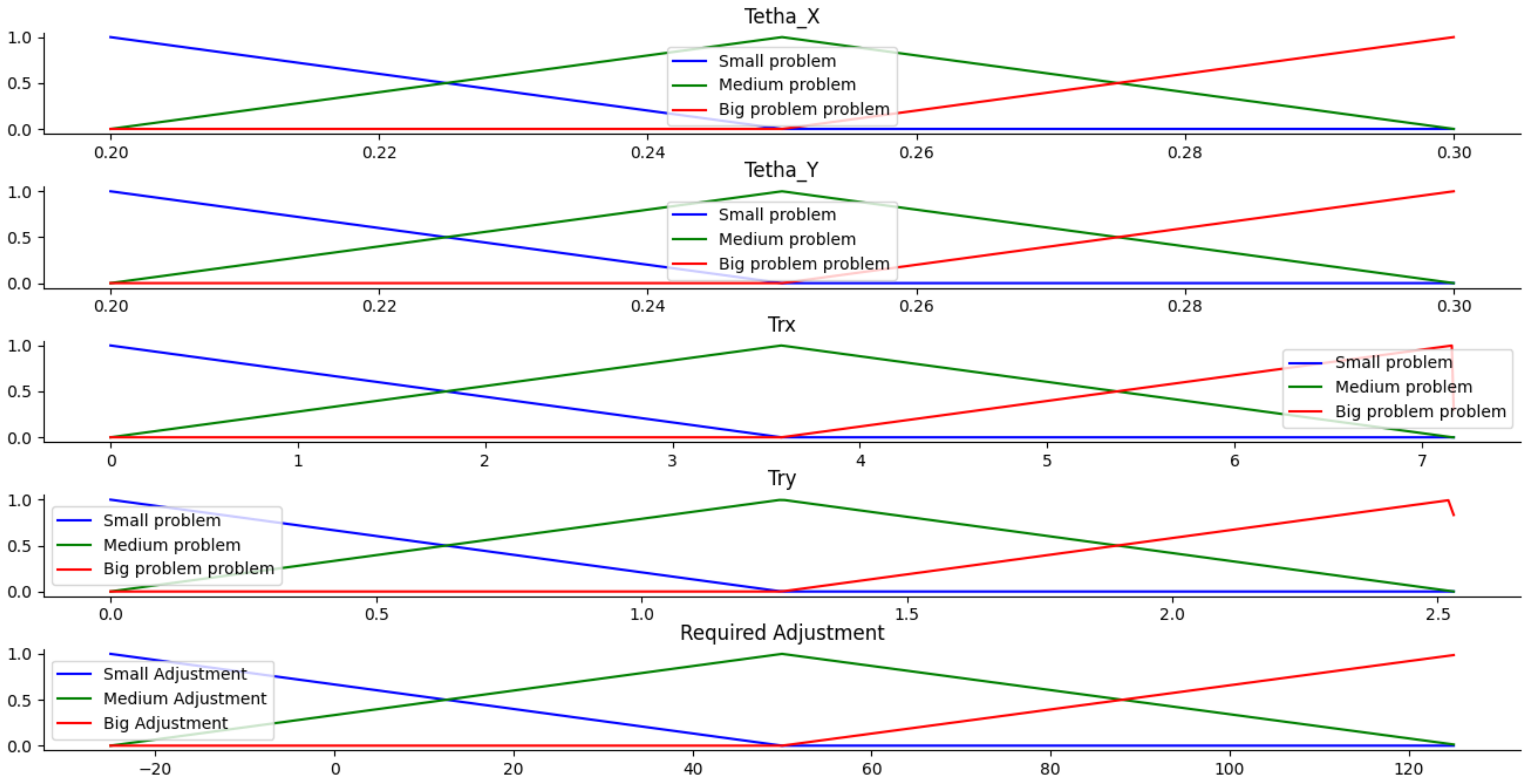


Figure 6-1 Membership functions

Table 6-1 Fuzzified values for each parameter

Parameter	Crisp input	Fuzzified Values		
		Small problem	Medium problem	Big problem
Tetha_X	0.1907	1	0	0
Tetha_Y	0.2499	0.0013	0.9987	0
Tr_x	6.9563	0.9423	0.0577	0
Tr_y	8.2802	1	0	0

6.2 Inference

An inference system in fuzzy logic is responsible for processing the fuzzified input values and making informed decisions based on a set of predefined rules. It utilizes the degrees of membership obtained from the fuzzification process to perform rule-based reasoning and determine the appropriate output values. This is typically done through a combination of logical operators such as AND, OR, and NOT, as well as aggregation methods such as minimum, maximum, or average.

To determine the membership values for the output parameter representing low-adjustment, the low problem membership values of all the input parameters are averaged. This yields a fuzzified value indicating a low modification requirement. The same approach is applied to determine the fuzzified values for medium and big adjustment, by averaging the corresponding membership values of the input parameters. The results of the inference system for the specific example under consideration are shown in **Table 6-2**.

Table 6-2 Results of the inference system

Parameter	Fuzzified Values		
	Small problem	Medium problem	Big problem
Tetha_X	1	0	0
Tetha_Y	0.0013	0.9987	0
Tr_x	0.9423	0.0577	0
Tr_y	1	0	0
Required Adjustment	0.7359	0.2641	0

6.3 Defuzzification

Defuzzification is interpreting the membership degrees of the fuzzy sets into a specific decision or real value. [24] It is the final step in the fuzzy logic system, where the fuzzy output is translated into a single representative value. The goal of defuzzification is to obtain a meaningful and easily interpretable crisp output value that reflects the overall information contained in the fuzzy sets. This allows for straightforward decision-making or further processing of the output.

Various techniques are available for defuzzification, each with its own characteristics and suitability for different scenarios. Some common defuzzification methods include the centroid method, the bisector method, and the middle of maximum methods.

Using the fuzzy output values, membership functions of the output parameters are chopped off. The area under the chopping line is then used to come up with the crisp value that is to be used for decision making. For the example under consideration, **Figure 6-2** represents this process.

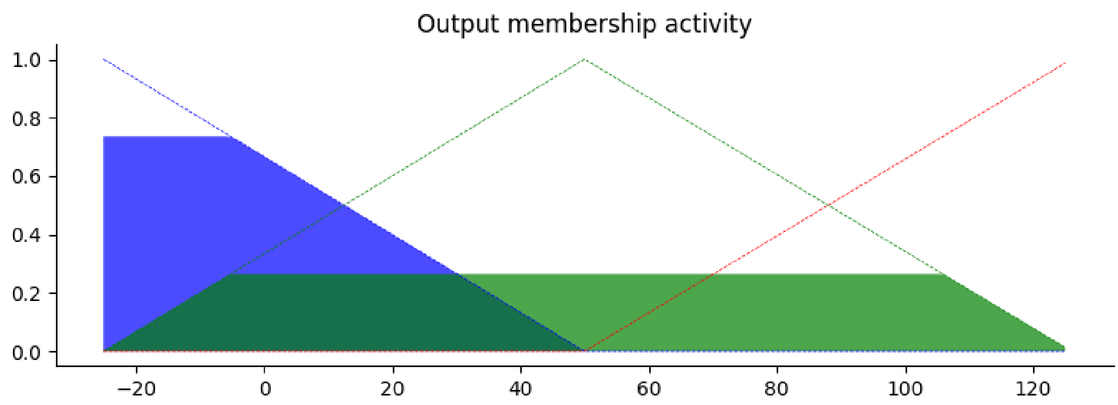


Figure 6-2 Chopped off output membership function

In the context of the fuzzy logic system used here, the centroid method is employed for defuzzification. The centroid method calculates the center of gravity, or centroid, of the chopped off output membership function. This is illustrated in **Figure 6-3**.

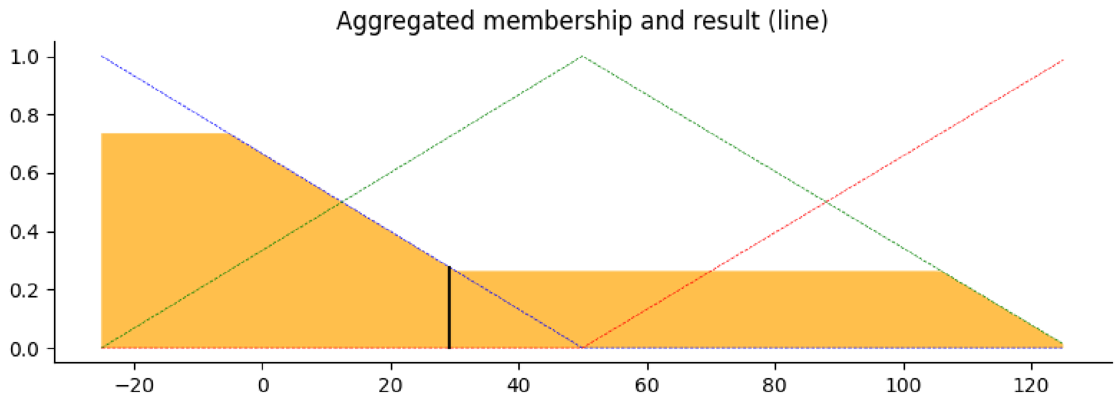


Figure 6-3 Crisp output value

In the centroid method, the crisp output value is determined by finding the point of intersection between the centroid and the horizontal axis. This intersection point represents the center of the fuzzy output distribution and serves as the crisp output value. The crisp output value for the example under consideration is found to be 29.3337. Which means, on a scale of 1 to 100, the modification required is around 30. The result shows that the structural modification required to solve the detected problems is relatively light. For the reason stated above, structural walls with relatively small planar length and thickness should be introduced into the model in order to solve stability and torsional rigidity problems of the building.

CHAPTER 7 CONCLUSIONS AND RECCOMENDATIONS

7.1 Conclusions

In conclusion, this thesis presented a software program capable of calculating parameters describing torsional regularity and stability of a structure. The software is designed to interact with conventional structural design software and provide the user with the required calculated values of torsional rigidity and stability parameters. The software is also capable of suggesting solutions to create an effective and sound structural system, by eliminating the need for excessive usage of structural members like walls. The developed graphical user interface makes it easier for users to interpret and apply the solutions suggested by the program.

The program is verified through an example replicated from the Eurocode example manual, and the results showed that the program works as intended. The program provides a much-needed solution to the problem of tedious and approximate methods of designing buildings for torsional rigidity and lateral stability. The programs' ability to create regular structures implies that, if the program is used widely, the number of structures that are more resistant to earthquake forces is going to grow larger and our society is more prepared to the unpredictable natural disasters.

7.2 Recommendations

Given the significance of these parameters, it is highly recommended that widely used structural design software incorporates the functionality of this program as one of their features to ensure the safety and economy of structures. Furthermore, it is highly recommended that structural designers use this program to create sound and economical buildings.

In addition, there is potential for the program to become even more powerful by incorporating the automation of all other design processes. With the automation of processes such as beam and column design, foundation design, and wall design, the software can provide a comprehensive and effective solution for structural design. This will not only save time and effort for the designer but also reduce the risk of human error.

The fuzzy logic based structural problem depth determination capacity of this program employed personal expertise for selecting the shape of membership functions. Through analysis done on multiple models and enquires targeting expertise of multiple structural designers, an object-oriented approach can be followed.

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APPENDIX

Six different modules were developed for the realization of the program. These six program modules were developed for the purpose of analysing required parameters, designing buildings, graphical user interface development and problem depth determination. The development of these modules is discussed on 3.3.

Providing the source code for all the developed modules would require an unrealistic amount of space. Instead, codes and code blocks which were used to carry out important tasks are presented tabularly. Sequential organization of the presented tables depicts the general working flow of the program.

Table 1 Source code for the development of Stability analysis module

Code	`import math`
Description	Python library for the purpose of list manipulation
Code	`import comtypes.client`
Description	Python library for the purpose of connecting with open ETABS instance
Code	`class DriftSeinsetivityCoefficientCalculator:`
Description	All drift sensitivity coefficient analysis algorithms are written under this class so as to be able to call the drift sensitivity analysis function from other modules.
Code	`helper = comtypes.client.CreateObject('ETABSv1.Helper')` `helper = helper.QueryInterface(comtypes.gen.ETABSv1.cHelper)` `myETABSObject = helper.GetObject("CSI.ETABS.API.ETABSObject")` `SapModel = myETABSObject.SapModel`
Description	Connect to open ETABS instance
Code	`ret = SapModel.SetPresentUnits(KN_m_C)`
Description	Change the current unit system into metric unit system.
Code	`if SapModel.GetModelIsLocked(): pass, else` `SapModel.Analyze.RunAnalysis()`
Description	Check weather analysis results are available and if not available, run analysis
Code	`def story_data_and_combination_list(self):`
Description	Generate story data and combination list for every combination in each direction and step type. These lists will later be appended with new columns with values of corresponding story drift and story force results.

Code	`[NumberofStories, StoryNames,StoryElevations , StoryHeights, IsMasterStory, SimilarToStory, SpliceAbove, SpliceHeight,ret] = SapModel.Story.GetStories()`
Description	get story data of the model
Code	`return Story_List, Story_Height_List, Combination_list_Design_X, Combination_list_Elastic_X, Combination_list_Design_Y, Combination_list_Elastic_Y, StoryNamesfordesignmodule`
Description	Return all the generated lists including story list, story height, design and elastic combination list.
Code	`def list_all_the_required_analysis_results(self):`
Description	From ETABS, extract story forces and story drift list for every combination in each direction and step type. These lists will later be appended with new columns with values of calculated drift sensitivity coefficient results.
Code	`ret=self.SapModel.Results.Setup. DeselectAllCasesAndCombosForOutput()`
Description	Deselect all the selected load cases and combos for extracting output results from ETABS.
Code	`[NumberResults, Story, LoadComb, StepType, StepNum, Direction, Drift, Label, dx, dy, dz,ret] = self.SapModel.Results.StoryDrifts()`
Description	From ETABS, extract story drift list for every combination in each direction and step type.
Code	`If Story_List[i]==Story[k] and Combination_list_Elastic_X[i]==LoadComb[k] and StepType[k]=="Max" and Direction[k]=="X": Story_Drift_X_Max_E.append(Drift[k])`
Description	Lookup for story drift results for corresponding combination in each direction and step type.
Code	`[GroupName, TableVersion, FieldsKeysIncluded, NumberRecords, TableData,ret] = self.SapModel.DatabaseTables.GetTableForDisplayArray('Story Forces',['Story','OutputCase','StepType','Location','P','VX' ,'VY'],'')`
Description	From ETABS, extract story force list for every combination in each direction and step type.
Code	`if Story_List[i]==TableData[k] and Combination_list_Design_X[i]==TableData[k+1] and TableData[k+2]=="Max" and TableData[k+3]=="Top": Vx_Max_Shear.append(TableData[k+5])`

Description	Lookup for story force results for corresponding combination in each direction and step type.
Code	`def Calculate _drift_seinsetivity_coefficient_Tetha_for_the_list(self):`
Description	The lists generated using previous codes are here analyzed using equation (1-3) to result in values of drift sensitivity coefficient results.
Code	`return Tetha_X_Max_List, Tetha_X_Min_List, Tetha_Y_Max_List, Tetha_Y_Min_List`
Description	Returns the list of drift sensitivity coefficient results for both X and Y directions for minimum and maximum step types.
Code	`def Table_for_report(self):`
Description	Under this definition(method), maximum values of drift sensitivity coefficient results are extracted for both directions and both step types.
Code	`return Tetha_X_Max_Reported_List, Combination_Repotred_List _Tetha_X_Max, Story_reported_List_Tetha_X_Max, Story_Height _Reported_List_Tetha_X_Max, StepType_Reported_List _Tetha_X_Max, Direction_Reported_List_Tetha_X_Max, Tetha_X_Min_Reported_List, Combination_Repotred_List_ Tetha_X_Min, Story_reported_List_Tetha_X_Min, Story_Height_Reported_List_ Tetha_X_Min, StepType_Reported_List_Tetha_X_Min, Direction _Reported_List_Tetha_X_Min, Tetha_Y_Max_Reported_List, Combination_Repotred_List_Tetha_Y_Max, Story_reported_List_ Tetha_Y_Max, Story_Height_Reported_List_Tetha_Y_Max, StepType_Reported_List_Tetha_Y_Max, Direction_Reported_List_ Tetha_Y_Max, Tetha_Y_Min_Reported_List, Combination_Repotred _List_Tetha_Y_Min, Story_reported_List_Tetha_Y_Min, Story_ Height_Reported_List_Tetha_Y_Min, StepType_Reported_List _Tetha_Y_Min, Direction_Reported_List_Tetha_Y_Min`
Description	Returns list of results to be reported to the user.

Table 2 Source code for the development of Torsional rigidity analysis module

Code	`import comtypes.client`
Description	Python library for the purpose of connecting with open ETABS instance
Code	`class DetermineTorsionalRigidityOfEachFloor`
Description	All torsional rigidity analysis algorithms are written under this class so as to be able to call the drift sensitivity analysis function from other modules.
Code	`helper = comtypes.client.CreateObject('ETABSv1.Helper')` `helper = helper.QueryInterface(comtypes.gen.ETABSv1.cHelper)` `myETABSObject = helper.GetObject("CSI.ETABS.API.ETABSObject")` `SapModel = myETABSObject.SapModel`
Description	Connect to open ETABS instance
Code	`ret = SapModel.SetPresentUnits(KN_m_C)`
Description	Change the current unit system into metric unit system.
Code	`[NumberofStories, StoryNames,StoryElevations , StoryHeights, IsMasterStory, SimilarToStory, SpliceAbove, SpliceHeight,ret] = SapModel.Story.GetStories()`
Description	get story data of the model
Code	`def Create_New_Load_Pattern_and_extract_mas_and_ stiffness_center(self):`
Description	Define three new load patterns for loads to be applied on a single story. The actions assigned on each story are force in the X direction, force in the Y direction, and rotation in the Z direction. As each story has to be assigned with three actions, there times the number of stroeys is the total number of defined load patterns. The mass center and stiffness center of the building are also formulated in an organized format.
Code	`if SapModel.GetModelIsLocked():ret = self.SapModel.SetModelIsLocked(False), else pass`
Description	Check weather ETABS model is locked and if the model is locked this unlocks the model. Unlocking the model is mandatory to be able to define new loadcases.
Code	`for i in range(len(Load_pattern_X_Y_RZ)):` `ret = self.SapModel.LoadPatterns.Add(Load_pattern_X_Y_RZ[i], 3, 0, True)`
Description	Defines all required load patterns on the ETABS model. Load_pattern_X_Y_RZ is a preorganized list containing all the list of required loadpatterns.
Code	`self.SapModel.Analyze.RunAnalysis()`
Description	ETABS analysis is started using this command.
Code	`[GroupName, TableVersion, FieldsKeysIncluded, NumberRecords, TableData_2,ret] = self.SapModel.DatabaseTables.GetTableFor`

	`DisplayArray('Centers Of Mass And Rigidity', ['Story', 'Diaphragm', 'XCCM', 'YCCM', 'XCR', 'YCR'], '')`
Description	Extracts all the required analysis results regarding the center of mass and center of rigidity of the building floor.
Code	`if self.StoryNames[i] == TableData_2[k]: Center_of_Mass_X_List.append(TableData_2[k + 2])`
Description	Organizes the list of center of mass in the x direction. This process is replicated for all other directions and for the center of rigidity list too.
Code	`for i in range(len(self.StoryNames)-1):` `    ret =self.SapModel.PointObj.AddCartesian(float(Center_of_Rigidity_X_List[i]), float(Center_of_Rigidity_Y_List[i]), float(self.StoryElevations[i + 1]),self.StoryNames[i+1]+"CR", self.StoryNames[i+1]+"CR")`
Description	Creates point objects on each floor. These point objects are created on the calculated center of rigidity of the floors.
Code	`for i in range(len(self.StoryNames) - 1):` `    ret = self.SapModel.PointObj.SetDiaphragm(self.StoryNames[i+1]+"CR", 3, self.StoryNames[i+1])` `    ret = self.SapModel.PointObj.SetLoadForce(self.StoryNames[i+1]+"CR", self.StoryNames[i+1]+"_X", [1000000,0,0,0,0,0], True)`
Description	Assigns storey diaphragm and lateral force in the X direction for the created point objects. Lateral force in the Y and rotational moment in the Z is also assigned following same procedures used.
Code	`return Load_Pattern_X_List, Load_Pattern_Y_List, Load_Pattern_RZ_List, Load_pattern_X_Y_RZ, Center_of_Mass_X_List, Center_of_Mass_Y_List, Center_of_Rigidity_X_List, Center_of_Rigidity_Y_List, Eccentricity_X_List, Eccentricity_Y_List`
Description	Returns all the generated lists regarding load patterns, center of mass, and center of rigidity.
Code	`def Get_Story_Displacement_and_Rotation_List(self):`
Description	Extract analysis results for the newly defined load patterns.
Code	`ret = self.SapModel.DatabaseTables.SetLoadCasesSelectedForDisplay(Load_pattern_X_Y_RZ)`

Description	Selects the list of load cases for which analysis results are to be extracted from.
Code	`[GroupName, TableVersion, FieldsKeysIncluded, NumberRecords, TableData_3, ret] = self.SapModel.DatabaseTables.GetTableForDisplayArray('Diaphragm Center Of Mass Displacements', ['Story', 'OutputCase', 'UX', 'UY', 'RZ'], '')`
Description	Extracts the analysis results regarding the Diaphragm center of mass displacements for the required load cases.
Code	`Displacement_XForce=[]` `for i in range(len(self.StoryNames) - 1):` `for k in range(0, len(TableData_3), 5):` `if self.StoryNames[i+1] == TableData_3[k] and (self.StoryNames[i+1]+"_X") == TableData_3[k+1]:` `Displacement_XForce.append(TableData_3[k + 2])` `else:` `pass`
Description	Organizes the analysis result obtained by looking up for results for the specific load case and storey under consideration. This process is repeated for actions in the Y and Z directions.
Code	`Stiffness_XForce = []` `for i in range(len(self.StoryNames) - 1):` `Stiffness_YForce.append(1/float(Displacement_XForce[i]))`
Description	Calculate the stiffness of each storey in the X direction. Stiffness in the Y direction and stiffness in the Z directions are also calculated using the same procedure.
Code	`rx = []` `for i in range(len(self.StoryNames) - 1):` `rx.append((float(Stiffness_ZRotation[i])/float(Stiffness_YForce[i]))**0.5)`
Description	Calculate the torsional radius in the X direction. Same procedure is used for calculating torsional radius in the Y direction.
Code	`return TableData_3, Displacement_XForce, Displacement_YForce, Rotation_ZRotation, rx, ry, Story_List`
Description	Returns the list of story center of mass displacement and rotation in all directions. Torsional radius in both the X and Y directions are also returned in a list format.

Tablee 3 Source code for the development of problem identification and solving module

Code	`class Torsional_Rigidity_and_Stability_Problem_Identifire _and_Solver_Class:`
Description	Problem identification and problem-solving algorithms are written under this class so as to be able to call these functionalities from other modules.
Code	`Problem_Index_Pair={"TTTTTT":"one",` `"TTTTTF":"two",` `"TTTTFT":"three",` `"TTTTFF":"four",` `"TTTFTT":"five",` `"TTTFTF":"six",…………}`
Description	64 different combinations of True and False results, defining the satisfaction of code impositions, are defined first. An index is also assigned for each problem type resulting in a dictionary.
Code	`ifmax(self.Tetha_X_Max_Reported_List+self.Tetha_X_Min_ Reported_List)<self.Target_Max_Tetha_In_X_DirectionPIS and max(self.Tetha_X_Max_Reported_List+self.Tetha_X_Min_Reported _List)>self.Target_Min_Tetha_In_X_DirectionPIS:` `Stability_problem_X="T"` `else:` `Stability_problem_X = "F"`
Description	Detects weather the stability in the X direction is within the limit specified by the user. Other parametric checks are also performed using same procedure to formulate the problem statement so the building model under consideration.
Code	`Building_Problem_Index=(self.Problem_Index_Pair[Building_ Problem_String[0]])`
Description	Identifies the building problem index form the defined dictionary of building problem index. Solutions that can fix the problems of the building are suggested using this index.
Code	`elif Building_Problem_Index == "six":` `if abs(Eccentricity_Y_Target_Floor) == Eccentricity_Y_ Target_Floor and abs(Eccentricity_X_Target_Floor) == Eccentricity_X_Target_Floor:` `Solution_1 = "Add_X_Direction_Wall_In_The_Top_And_ Y_Direction_Wall_In_The_Right_Side_Of_The_Building"` `Solution_2 = "Thicken_X_Direction_Wall_In_The_Top_And_ Y_Direction_Wall_In_The_Right_Side_Of_The_Building"` `Solution_3 = "Add_Y_Direction_Wall_In_The_Right_And_ X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The_ Building"` `Solution_4 = "Thicken_Y_Direction_Wall_In_The_Right_And_`

	`` X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The_ Building" elif abs(Eccentricity_Y_Target_Floor) == Eccentricity_Y _Target_Floor and abs(Eccentricity_X_Target_Floor) != Eccentricity_X_Target_Floor: Solution_1 = "Add_X_Direction_Wall_In_The_Top_And_ Y_Direction_Wall_In_The_Left_Side_Of_The_Building" Solution_2 = "Thicken_X_Direction_Wall_In_The_Top_And_ Y_Direction_Wall_In_The_Left_Side_Of_The_Building" Solution_3 = "Add_Y_Direction_Wall_In_The_Right_And_ X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building" Solution_4 = "Thicken_Y_Direction_Wall_In_The_Right_And_ X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building" elif abs(Eccentricity_Y_Target_Floor) != Eccentricity_Y _Target_Floor and abs(Eccentricity_X_Target_Floor) == Eccentricity_X_Target_Floor: Solution_1 = "Add_X_Direction_Wall_In_The_Bottom_And_ Y_Direction_Wall_In_The_Right_Side_Of_The_Building" Solution_2 = "Thicken_X_Direction_Wall_In_The_Bottom_And_ Y_Direction_Wall_In_The_Right_Side_Of_The_Building" Solution_3 = "Add_Y_Direction_Wall_In_The_Left_And_ X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building" Solution_4 = "Thicken_Y_Direction_Wall_In_The_Left_And_ X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building" elif abs(Eccentricity_Y_Target_Floor) != Eccentricity_Y _Target_Floor and abs(Eccentricity_X_Target_Floor) != Eccentricity_X_Target_Floor: Solution_1 = "Add_X_Direction_Wall_In_The_Bottom_And_ Y_Direction_Wall_In_The_Left_Side_Of_The_Building" Solution_2 = "Thicken_X_Direction_Wall_In_The_Bottom_And_ Y_Direction_Wall_In_The_Left_Side_Of_The_Building" Solution_3 = "Add_Y_Direction_Wall_In_The_Left_And_X _Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building" Solution_4 = "Thicken_Y_Direction_Wall_In_The_Left_And_ ```

	`X_Direction_Wall_In_The_Top_and_Bottom_Side_Of_The _Building"`
Description	Checks parametric data of the model regarding lateral stability and torsional rigidity and then suggests effective and robust structural solution to the problem of the model. Only solution determination for model index four is shown here.
Code	`return Building_Problem, Building_Problem_String, Building_Problem_Index, Solution_1, Solution_2, Solution_3, Solution_4, Eccentricity_X_Target_Floor, Eccentricity_Y_ Target_Floor, Torsional_Radius_X_Target_Floor, Torsional_Radius_Y_Target_Floor`
Description	Returns identified structural problems and solution suggestions that can fix the detected structural problems.