COMPARATIVE STUDY ON SEISMIC ANALYSIS OF BUILDINGS FOR DIFFERENT CODE OF PRACTICES COMMONLY USED IN SRI LANKA

K.P.N. Prasanna

(118624N)

Degree of Master of Engineering in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa
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March 2016

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other university or institute of higher learning and to the best of my knowledge and believe it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ACKNOWLEDGEMENT

There are many people, who have contributed in making this research and the accompanying thesis a reality, to whom I am very grateful.

Firstly, I would like to express my deepest gratitude to Dr. C.S.Lewangamage, senior lecturer of the Department of Civil Engineering of University of Moratuwa and also the supervisor of this research, for his constant support to complete this research successfully. It is indeed his guidance, enthusiasm, constructive suggestions, encouragements and invaluable assistance provided throughout the project duration made this thesis possible.

My special thanks go to Prof. M.T.R. Jayasinghe, the former head of the Department of Civil Engineering of University of Moratuwa for making me interested in the field of seismology.

I would also like to express my gratitude to all other members of the academic and non-academic staff of the Department of Civil Engineering of University of Moratuwa, for their support extended towards me in various means to finalize this project successfully.

Finally, I wish to express my appreciation to my family members and friends for their assistance and encouragement given to me in completing this project.

ABSTRACT

Earthquake threat has been identified by many countries and analysis and design against seismic effects have therefore become almost a basic part of their structural design process. Sri Lanka has also identified the importance of designing buildings against seismic actions, specially due to recent incidents, which took place in and around the Island. However, Sri Lanka does not have its own code of practice for designing against seismic actions. Also there are not many established guidelines available in the country for this purpose. As a result, when it is required to analyze and design buildings against seismic actions, the engineers and scientists in the country face difficulties, basically with which codes and guidelines to follow. It is obvious that all of those codes are not equally suitable for conditions in Sri Lanka and also will not give out similar results.

The aim of this research is to check the performance level that a building can achieve when analyzed according to different codes of practice, which are commonly used in Sri Lanka in seismic analysis. In this context, three codes of practice were considered, taking into account their applicability over the others in Sri Lankan context, namely the Australian code (AS1170.4-2007), the Indian code (IS 1893 (Part 1):2002) and the Euro code (BS EN-1998-1:2004). The recommendations provided in the research, conducted by the University of Moratuwa, Sri Lanka, aimed at providing guidance on suitable analysis procedures for buildings in Sri Lanka, based on the euro code were also inco-operated in the analysis.

First, the seismic analysis procedures outlined in those codes with respect to both static and dynamic analysis were discussed in detail. Then, the analysis procedures introduced in the respective codes of practice were compared and contrasted, considering how they handle the major effects, characteristics of the structures and geotechnical considerations etc.

In order to demonstrate the analysis procedures and to make a comparison on results, three high-rise buildings, having floors between 10 to 20 were selected and analyzed according to the guidelines provided in the three selected codes of practice respectively. In this case, all the structures were analyzed for three different soil conditions, which could be found in Sri Lanka. The computer software "ETABS" has been used for finite element modeling of all the structures. Response Spectrum Analysis (RSA) was used in all the dynamic analysis purposes. Equivalent static analysis was also carried out as per requirements, established in particular codes of practice.

According to the results obtained in the analysis, it has been found that, irrespective of the code of practice, which has been used in the analysis, the structures have achieved Immediate Occupancy Level (IOL)in all twenty seven cases, according to FEMA356 standards. It was also found that the Indian code has given the highest drift values in many occasions while the Euro code also has given very close or sometimes similar drift values. In contrast, the Australian code has generally resulted lowest drift values. Further, it has also been identified that the Euro code has given the highest design base shear forces in all eighteen occasions. On the other hand, the Indian code has given lowest design base shear force in many occasions. The Australian code has also shown the lowest design base shear forces in few occasions.

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1.0 INTRODUCTION

1.1 Background

It has now been realized that Sri Lanka can no longer be considered isolated from seismic threat when the recent past events occurred in and around the island are considered. Therefore, the higher authorities, scientists and engineers in the relevant fields have taken the initiative to study the possible earthquakes in Sri Lanka and their adverse effects [5].

Since, Sri Lanka is located at a reasonable distance from the Indo-Australian plate boundary, it has not been facing a big threat against inter-plate type earthquakes.

Other than inter-plate earthquakes, that can happen at plate boundaries, intra-plate earthquakes can also take place within the tectonic plates, causing significant damages. Therefore, the scientists and engineers in the country have identified the importance of designing structures against possible earthquakes, that can happen in the future. However, in Sri Lanka, there is not much established guidelines available for analysis and designing of buildings against seismic actions. The engineers and scientists face difficulties basically with what code of practice to follow and how to apply the other codes for Sri Lankan conditions.

Furthermore, dynamic analysis has become increasingly popular among many countries and most of the seismic codes have specified that the dynamic analysis as the preferred procedure for structural analysis, because of its superiority in reflecting seismic response accurately, specially in tall buildings and irregular buildings.

One main nature of dynamic analysis is its high sensitivity to the characteristics of ground motions selected and engineering assumptions made, which in turn are dependent on the experience and judgment of the analyst. Studies in the past have shown that distinctly different results could be obtained from analysis of the same building conducted by different analysts. Therefore, dynamic analysis procedures were regarded as unsafe, unless conducted by experienced and knowledgeable engineers [7]. This reiterates the importance of explicit knowledge of the ground condition of the location, validity of assumptions, availability of seismic data particular to the location etc, when dealing with dynamic analysis.

Since there is no own code of practice for seismic analysis, the engineers of Sri Lanka have to use one of available codes among many. But, it is clear that each of these codes are not equally convenient and suitable to be applied in Sri Lankan conditions and would not give same results after analysis. These codes are prepared to suit with their geotechnical conditions, environment and structures. Therefore it is very important and useful to make a detail discussion and study through these codes to check the applicability of these codes for Sri Lankan conditions and to check results through some analysis.

1.2 Scope of the study

Since, most of the buildings, which can be found in Sri Lanka are reinforced concrete buildings, the research has been limited to reinforced concrete buildings only. Further, very tall buildings are also not common in the country, except there are few located in Colombo. Buildings of mid-height are common and can be found in almost all the major cities in the Island. Therefore, the research to be more useful, buildings between ten to twenty floor levels were selected. The analysis procedure was also limited for linear methods only.

1.3 Objectives

The main objectives of this research can be pointed out as,

* To discuss and compare the seismic analysis procedures described in the Australian code (AS1170.4-2007), the Indian code (IS 1893 (Part 1):2002) and the Euro code (EN 1998-1:2004).
* To demonstrate through case studies how to apply the static and dynamic seismic analysis procedures described in selected codes to analyse buildings in Sri Lanka under different geotechnical considerations.
* To compare the performance level that can be achieved through analysis against three of these codes separately.

1.4 Methodology

Firstly, three main seismic analysis codes that are often used by Sri Lankan engineers were identified, namely the Euro code, EC-8 (EN 1998-1:2004), the Australian code (AS 1170.4-2007) and the Indian code (IS 1893 (Part 1):2002). In literature review section, the analysis procedures that have been established in each of those codes were then outlined in step by step.

To demonstrate the analysis procedures established in above codes of practice, three reinforced concrete buildings of floors between ten to twenty were selected and analysed according to the guidelines provided in respective codes of practice.

In order the results to be more fair and general, the analysis were repeated for different geotechnical conditions, that can be commonly found in Sri Lanka.

Finally, the structural performance level, that has been reached, when analysed according to different codes of practice were found and compared.

The methodology adopted in this study has been described in detail in Chapter 3.

1.5 Arrangement of the report

The remainder of the report is divided into the following sections.

Chapter 2- This chapter basically outlines the seismic analysis procedures established in codes of practice that are commonly used in seismic analysis in Sri Lanka, namely the Euro code (EN 1998-1:2004) with national guide lines developed for seismic analysis of buildings in Sri Lanka by Disaster Management Centre (DMC), Sri Lanka, the Australian code (AS 1170.4-2007) and the Indian code (IS 1893 (Part 1):2002.

At latter part of the chapter, it also compare and contrast the analysis procedure described in each code of practice, how they have defined different parameters and how they have considered different structural effects etc.

Chapter 3- This chapter basically describes the methodology adopted to achieve objectives of the study.

It describes how the three codes of practice were selected for analysis.

It also explains the selection of buildings for analysis.

It further describes the soil categories that the analysis to be based on for Sri Lankan conditions

Chapter 4- This chapter basically presents step by step calculations of seismic analysis adopted according to the Euro code (EN1998-1:2004) for selected reinforced concrete buildings.

It explains basic characteristics of ETABS computer models, developed to fulfill the requirements established in the code.

It describes the implementation of static method of analysis to obtain base shear force and steps to follow to distribute this force at each floor level.

It also describes in detail the procedure adopted to obtain seismic response quantities dynamically by Response Spectrum Analysis (RSA).

It further demonstrate the established method to check the structure against damage limitation requirements and against allowable inter-storey drift coefficient.

Chapter 5- In similar way as described in Chapter 4, The Chapter 5 basically presents step by step calculations of seismic analysis adopted according to the Australian code (AS 1170.4-2007) for selected reinforced concrete buildings.

It explains basic characteristics of ETABS computer models, developed to fulfill the requirements established in the code, the procedures described with respect to static and dynamic(RSA) analysis to obtain response quantities and its vertical distribution etc.

It further demonstrates the established method to check the structure against damage limitation requirements and against allowable inter-storey drift coefficient.

Chapter 6- As similar in Chapter 4 and Chapter 5, The Chapter 6 basically presents step by step calculations of seismic analysis adopted according to the Indian code (IS 1893 (Part 1) : 2002) for selected reinforced concrete buildings.

It explains basic characteristics of ETABS computer models, developed to fulfill the requirements established in the code, the procedures described with respect to static and dynamic(RSA) analysis to obtain response quantities and its vertical distribution etc.

It further demonstrates the established method to check the structure against damage limitation requirements.

Chapter 7 - This chapter basically provides a detail comparison of performance levels achieved by buildings analysed with different codes of practice.

Chapter 8 - Conclusions made on analysis results and recommendations are described in this chapter.

2.0 LITERATURE REVIEW

Analysis of structures for seismic effects has now become almost a basic part of the structural design procedures almost all over the world. To achieve this purpose, some countries have developed their own codes of practice and they therefore analyse and design the structures accordingly. However, for countries those who do not have their own codes of practice have to depend upon some other codes of practice which can be used for their purposes with appropriate adjustments.

Sri Lanka also does not have its own code of practice for seismic analysis. This chapter presents a detail analysis and discussion made on three codes of practice, which are commonly used in seismic analysis in Sri Lanka, namely the Euro code (EN 1998-1:2004) with national guidelines developed for seismic analysis of buildings in Sri Lanka by Disaster Management Centre (DMC), Sri Lanka, the Australian code (AS 1170.4-2007) and the Indian code (IS 1893 (Part 1):2002.

Firstly the analysis procedures established in all three codes were out lined in brief, highlighting how those codes are used in analysis process in Sri Lanka. Then those three codes of practice were compared and contrasted under different criteria considering how those codes have defined different parameters and how they have proposed values for them etc, which is very important to find out the advantages and disadvantages of adopting one code over the other.

2.1 Analysis procedure as described in Euro code (EN 1998-1:2004)

This section describes briefly the analysis procedure, which has been established in Euro code. It should be also mentioned that the national guidelines developed for seismic analysis of buildings in Sri Lanka by Disaster Management Centre (DMC), Sri Lanka have also been inco-operated in the same section.

2.1.1 Design seismic action

The structures shall be designed to fulfill the two fundamental requirements; no-collapse requirement and damage limitation requirement, as stated in EN 1998-1:2004 (EC 8). The proposed peak ground acceleration values will represent the seismic action for no-collapse requirement and they will be different for buildings of different importance classes.

Table EN-1: Classification of buildings into important classes

Importance level	Classification	Examples
I	Buildings of minor importance for safety of public and other property	Agricultural buildings, isolated structures, domestic structures
II	Buildings of low-moderate importance for safety of public and other properties	Hotels, offices, apartment buildings of less than 10 storeys high, Factories up to 4 storeys high Car parking buildings, Shopping centres less than 10,000m^2 gross area , Public assembly buildings for fewer than 100 persons Emergency medical and other emergency facilities not designated as post-disaster, Airport terminals, principal railway stations
III	Buildings of significant importance for safety of public and other properties	Hotels, offices, apartment buildings over 10 storeys high, Factories and heavy machinery plants over 4 storeys high Shopping centres of over 10000m^2 gross area excluding parking, Public assembly buildings for more than 100 persons
IV	Buildings of greater importance with post disaster functions for civil protection	Pre-schools, Schools, colleges, universities, Major infrastructure facilities, e.g. power stations, substations Medical facilities for surgery and emergency treatment, Hospitals, Fire and police stations, Ambulance facilities Buildings housing toxic or explosive substances in sufficient quantities to be dangerous to the public if released Extreme hazard facilities (Dams etc.)

The structures shall be classified into four categories (Table EN-1). The importance class I includes the structures which does not require an explicit seismic consideration in the design process. The importance class II, III and IV include the structures identified as important during an earthquake event considering their function, the consequences of failure and the economic aspects. Therefore, importance class II, III and IV buildings shall be designed for seismic actions having 475, 1500 and 2500 year return periods respectively [5].

The design peak ground acceleration value for each category of buildings shall be then calculated as

$$a_g = \gamma_1 . a_{g,475}$$

Where,

a_g : Design peak ground acceleration

γ_1 : Importance factor (Refer Table EN-2)

$a_{g,475}$: Peak ground acceleration for 475 years return period seismic action (Refer Table EN-2: Note)

Table EN-2 : Design peak ground acceleration values (a_g)

Importance Class	γ_1
I	--
II	1
III	1.5
IV	1.8
Note: For Sri Lanka, the (reference) peak ground acceleration for475 year return period shall be taken as 0.1g and is assumed same for the whole country [5].	

2.1.2 Horizontal elastic response spectra

It has been recommended that the horizontal elastic response spectra given in IS 1893 (Part 1): 2002 to be used in the seismic analysis according to Euro code for buildings in Sri Lanka [5], and expressed by

$$0.00 \leq T \leq T_B S_e(T) = \ 1 + 15T$$

$$T_B \leq T \leq T_C S_e(T) = \ 2.5$$

$$T_C \leq T \leq 4.00 \qquad S_e(T) = \ S/T$$

Where

$S_e(T)$: elastic response spectra

T : vibration period of a linear single-degree-of-freedom system

T_B : lower limit of the period of the constant spectral acceleration branch

T_C : upper limit of the period of the constant spectral acceleration branch

S : soil factor

The horizontal elastic response spectra are given for three types of soil classified based on the Standard Penetration Test value (N_{SPT}) [5]. Refer table EN-3 for the soil classification and the corresponding parameters defining the elastic response spectra.

Table EN-3 :Soil classification and parameters defining horizontal elastic response spectra

Soil Type	N_{SPT}	S	T_B	T_C
I (Hard soil)	>30	1	0.1	0.4
II (Medium soil)	10-30	1.36	0.1	0.55
III (Soft soil)	<10	1.67	0.1	0.67

2.1.3 Horizontal design response spectra

The design response spectrum for the seismic analysis of buildings shall be obtained by reducing the elastic response spectra by the value of behavior factor (q) as recommended in EC 8 and are given in the specific sections of the code. The design response spectra shall be then given as

$$0.00 \leq T \leq T_B S_d(T) = (1 + 15T)/q$$

$$T_B \leq T \leq T_C S_d(T) = 2.5/q$$

$$T_C \leq T \leq 4.00 \qquad S_d(T) = (\frac{S}{T})/q$$

Where

$S_d(T)$: design horizontal response spectrum

q : behavior factor

T, T_B, T_C, S: as defined in Section 2.1.2 above

In selecting the behavior factors, the buildings of importance class II, III and IV shall be considered as ductility class medium (DCM) or high (DCH).

The behavior factor (q) used in the reinforced concrete structures as given in EN 1998-1/5.2.2.2 is given by

$$q = q_0 k_w \geq 1.5$$

Where

q: behavior factor

q_0: basic value of the behavior factor (Refer Table EN-4)

k_w: factor reflecting the prevailing failure mode in structural systems with walls (Refer Table EN-5)

Table EN-4 :Basic value of the behavior factor (q_0) for systems regular in elevation (EN 1998-1:2004/5.2.2.2 (Table 5.1))

Structural Type[1]	DCM	DCH
Frame system, dual system, coupled wall system	3.0 α_u/α_1	4.5 α_u/α_1
Uncoupled wall system	3.0	4.0 α_u/α_1
Torsionally flexible system	2.0	3.0
Inverted pendulum system	1.5	2.0
1. For the definition of each structural type refer EN 1998-1/5.2.2.1		
2. For buildings which are not regular in elevation, the value of q_0 shall be reduced by 20%.		

α_u and α_1 are defined in EN 1998-1/5.2.2.2 (4) as

α_1: the value by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any member in the structure, while all other design actions remain constant

α_u: the value by which the horizontal seismic design action is multiplied, in order to form plastic hinges in a number of sections sufficient for the development of overall structural instability, while all other design actions remain constant (This value may be obtained from a nonlinear static (pushover) global analysis)

In the absence of the calculated value of the multiplication factor α_u/α_1 as above, EN 1998-1/ 5.2.2.2 (5) gives approximate values for buildings regular in plan (Refer Table EN-6)

Table EN-5 : Factor k_w reflecting the prevailing failure mode(EN 1998-1:2004/5.2.2.2 (11)P)

Structural Type[1]	k_w
Frame and frame-equivalent dual systems	1.00
Wall, wall-equivalent and Torsionally flexible systems	$0.5 \leq \frac{1+\alpha_0}{3} \leq 1$

1. For definitions of structural types refer EN 1998-1/5.2.2.1
2. α_0 is the prevailing aspect ratio of the walls of the structural system and if the aspect ratios h_{wi}/l_{wi} of all walls *i* of a structural system do not significantly differ, the prevailing aspect ratio shall be determined as (EN 1998-1/5.2.2.2 (12))

$$\alpha_0 = \sum h_{wi} / \sum l_{wi}$$

Where

h_{wi}: height of the wall *i*

l_{wi}: length of the section of wall *i*

Table EN-6 : Approximate values for multiplication factor α_u/α_1 for buildings regular in plan (EN 1998-1:2004/5.2.2.2 (5))

Structural Type	α_u/α_1
Frames or frame-equivalent dual systems	
One-storey buildings	1.1
Multistory, one bay frames	1.2
Multistory, multi bay frames or frame-equivalent dual systems	1.3
Wall or wall-equivalent dual systems	
Wall systems with only two uncoupled walls per horizontal direction	1.0
Other uncoupled wall systems	1.1
Wall-equivalent dual, or coupled wall systems	1.2

2.1.4 Vertical component of the seismic action

EN 1998-1: 2004/4.3.5.2 states that If $a_{vg} is greater$ than 0.25 g (2.5m/s²) the vertical component of the seismic action should be taken into account in the cases listed below.

- For horizontal or nearly horizontal structures members spanning 20m or more;
- For horizontal or nearly horizontal cantilever components longer than 5m;
- For horizontal or nearly horizontal pre-stressed components;
- For beams supporting columns:
- In base-isolation systems;

It is recommended to use the vertical elastic response spectrum recommended in IS 1893-1:2002, where 2/3 of horizontal elastic response spectrum as vertical elastic response spectra [5].

2.1.5 Seismic analysis of buildings

2.1.5.1 Seismic mass of the building

EN 1998-1: 2004/3.2.4 states that seismic mass of the building which is taken into account in evaluating the inertial effects of the design seismic action is in the following combination of actions.

$$\sum G_{k,j} + \sum \psi_{E,i} \,.\, Q_{k,i}$$

Where

$G_{k,j}$: permanent load

$Q_{k,i}$: variable load

$\psi_{E,i} = \psi_{2,i}\varphi$(EN 1998-1: 4.2.4)

$\psi_{2,i}$: factor representing the quasi permanent value of the variable action (EN 1990:2002 - Table EN-7)

φ : (EN 1998-1: Table 4.2- Refer Table EN-9)

2.1.5.2 Seismic load combination

The seismic load combination to be used in the analysis and design of buildings shall be taken as the load combination given in EN 1990: Basis for designs

$$\sum G_{k,j} + A_{E,d} + \sum \psi_{2,i} Q_{k,i}$$

Where,

G : permanent actions (self-weight and other dead loads)

A : design seismic action

Q : variable actions (live loads)

$\psi_{2,i}$: factor representing the quasi permanent value of the variable action (EN 1990:2002 - Table EN-7)

Table EN-7 : Recommended values of ψ factors in EN 1990/Table A1.1

Action	Ψ_0	Ψ_1	Ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)			
Category A : domestic, residential areas	0,7	0.5	0.3
Category B : office areas	0,7	0.5	0.3
Category C : congregation areas	0,7	0.7	0.6
Category D : shopping areas	0,7	0.7	0.6
Category E : storage areas	1,0	0.9	0.8
Category F : traffic area, vehicle weight _ 30kN	0,7	0.7	0.6
Category G : traffic area, 30kN < vehicle weight _ 160kN	0,7	0.5	0.3
Category H : roofs	0	0	0
Snow loads on buildings (see EN 1991-1-3)*			
Finland, Iceland, Norway, Sweden	0.7	0.5	0.2
Remainder of CEN Member States, for sites located at altitude H > 1000 m a.s.l.	0.7	0.5	0.2
Remainder of CEN Member States, for sites located at altitude H _ 1000 m a.s.l.	0.5	0.2	0
Wind loads on buildings (see EN 1991-1-4)	0.6	0.2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0.6	0.5	0

Ψ_0 represents combination value of the variable action
Ψ_1 represents frequent value of the variable action
Ψ_2 represents quasi-permanent value of the variable action

For different categories of actions (A,B etc…), Refer Table EN-8

Table EN-8 : Definitions of different categories A-E

Category	Specific Use	Examples
A	Areas for domestic and residential activities	Rooms in residential buildings and houses; bedrooms and wards in hospitals; bedrooms in hotels and hostels kitchens and toilets.
B	Office areas	
C	Areas where people may congregate (with the exception of areas defined under category A, B and D1)	C1: Areas with tables, etc e.g. areas in schools, cafes, restaurants, dining halls, reading rooms, receptions C2: Areas with fixed seats, e.g. areas in churches, theatres or cinemas, conference rooms, lecture halls, assembly halls, waiting rooms, railway waiting rooms. C3: Areas without obstacles for moving people, e.g. areas in museums, exhibition rooms, etc. and access areas in public and administration buildings, hotels, hospitals, railway station forecourts C4:Areas with possible physical activities, e.g. dance halls, gymnastic rooms, stages. C5:Areas susceptible to large crowds, e.g. in buildings for public events like concert halls, sports halls including stands, terraces and access areas and railway platforms.
D	Shopping areas	D1: Areas in general retail shops D2: Areas in department stores.
E1	accumulation of goods,	Areas for storage use including storage of books and other documents
E2	Industrial use	

Table EN-9 : Values of φ factors

Type of available action	Storey	φ
Categories A-C	Roof	1.0
	Storeys with correlated occupancies	0.8
	Independently occupied storeys	0.5
Categories D-F and archives		1.0

2.1.5.3 Structural Regularity

The buildings shall be categorized as regular or irregular according to provisions given in EN 1998-1: 2004/4.2.3.

2.1.5.3.1 Criteria for regularity in plan

The criteria for regularity in plan are described in EN 1998-1:2004/4.2.3.2. The following conditions shall be checked in order to categorize the selected structure is regular in plan.

- Lateral stiffness and the mass distribution shall be approximately symmetrical in plan with respect to two orthogonal axes
- The plan configuration shall be compact.
- The slenderness $\lambda = L_{max}/L_{min}$ of the building in plan shall not be greater than 4.
- The structural eccentricity e_{c0} and the torsional radius, r (at each level and for each direction of analysis) shall be

X-direction; $e_{0x} \leq 0.3r_x$

$r_x \geq l_s$

Y-direction; $e_{0y} \leq 0.3r_y$

$r_y \geq l_s$

For definitions of the centre of stiffness and of the torsional radius in multi storey buildings refer "Manual for the seismic design of steel and concrete buildings to Euro Code 8".

2.1.5.3.2 Criteria for regularity in elevation

A building must satisfy all the requirements given in Clause 4.2.3.3 of EN 1998-1:2004 to be classified as regular in elevation. The requirements are briefed here as follows.

- All the vertical load resisting elements shall continue uninterrupted from foundation level to the top of the building or where set backs are present to the top of the setback.
- Mass and stiffness shall either remain constant with height or reduce only gradually without abrupt changes.
- In buildings with moment-resisting frames, the lateral resistance of each storey (i.e. the seismic shear initiating failure within that storey, for the code-specified distribution of seismic loads) shall not vary 'disproportionately' between storeys.
- Buildings with setbacks (i.e. where the plan area suddenly reduces between successive storeys) are generally irregular, but may be classified as regular if additional condition defined in the EC 8 are satisfied.

2.1.5.4 Structural Analysis

Clause 4.3.3 of EN 1998-1: 2004 describes two types of linear-elastic analysis as

I. Lateral force method of analysis (Static)

II. Modal response spectrum analysis (Dynamic)

a) The use of above two methods of analysis shall be decided based on the structural characteristics of the building.

b) For the consequences of structural regularity on the structural analysis method refer Table EN-10 (EN 1998-1:2004/ Table 4.1)

c) The criteria given in EN 1998-1: 2004/ 4.3.1 shall be considered in the structural model used in the analysis

Table EN-10 : Consequences of structural regularity on structural model and the analysis method

Regularity		Allowed simplification		Behavior factor
Plan	Elevation	Model	Linear-elastic analysis	(for linear analysis)
Yes	Yes	Planar	Lateral Force	Reference value
Yes	No	Planar	Modal	Decreased value
No	Yes	Spatial	Lateral Force	Reference value
No	No	Spatial	Modal	Decreased value

2.1.5.4.1 Static lateral force method of analysis

a) The static lateral force method of analysis is used for buildings only which satisfy the requirements given in EN 1998-1:2004/4.3.3.2.1 (2).

b) The total seismic base shear of the building shall be determined by the following expression (See EN 1998-1:2004/eq.4.5).

$$F_b = S_d(T_1).m.\lambda$$

Where

$S_d(T_1)$: the spectral acceleration obtained from the design response spectrum for the fundamental period of vibration T_1.

m: the seismic mass of the building (Refer Clause 3.2.4 of EN 1998-1:2004)

λ: correction factor as given in EN 1998-1:2004/ 4.3.3.2.2

T_1: fundamental period of vibration of the building as given in EN 1998-1:2004/4.3.3.2.1 (2), (3), (4) & (5).

c) The total horizontal load shall then be distributed over the height of the building. Normally the distribution of lateral loads shall be done by making simple assumption on the mode shape, that is, for regular buildings, the mode shape is a straight line of which the displacement is directly proportional to the height (fundamental mode of vibration). With this assumption, the force at storey level F_k shall be determined as (EN 1998-1:2004/eq.4.10)

$$F_k = F_b \frac{z_i m_i}{\Sigma z_j m_j}$$

Where z_i and zj represent the heights of the masses m_i, m_j above the level of application of the seismic action.

2.1.5.4.2 Modal response spectrum analysis

a) This type of analysis is generally recommended to use for any building. The followings are the important aspects that should be considered in the analysis procedure in accordance with the code.

b) The response of all modes of vibration contribution significantly to the global response shall be considered. The code specifies that, this requirement is taken to be satisfied if

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

c) Combination of modal responses is an important step in the modal response spectrum analysis. EN 1998-1:2004/4.3.3.3.2 recommends the "Complete Quadratic Combination" (CQC) rule as an accurate procedure for this. The results of the modal analysis in each direction are then combined by the recommended methods as described in EN 1998-1:2004/4.3.3.5.1.

d) EC 8 recommends the accidental torsional effects to be taken into account in the seismic analysis whenever a spatial model is used.

2.1.5.5 Accidental torsional effects

In order to account for uncertainties in the location of masses and in the special variation of the seismic motion, as described in EN 1998-1:2004/4.3.2, the calculated centre of mass at each floor level *i* shall be considered as being displaced from its nominal location in each direction by an accidental eccentricity:

$e_{ai} = \pm 0.05.\ L_i$

where

e_{ai} is the accidental eccentricity of storey mass i from its nominal location, applied in the same direction at all floors;

L_i is the floor-dimension perpendicular to the direction of the seismic action.

Whenever a spatial model is used for analysis, as described in clause 4.3.3.3.3 of EN 1998-1:2004, the accidental torsional effects may be determined as the envelop of the effects resulting from the application of static loadings, consisting of sets of torsional moments M_{ai} about the vertical axis of each storey *i*:

$M_{ai} = e_{ai}.F_i$

2.1.5.6. Displacements and drift

2.1.5.6.1 Displacement

As described in EN 1998-1:2004/4.3.4, in the case of a linear analysis the displacement of a point of the structural system induced by the design seismic action is calculated by the product of displacement behavior factor and the displacement of the same point of the structural system as determined from the linear analysis.

$d_s = q_d d_e$

2.1.5.6.2 Inter-storey drift

EN 1998-1:2004/4.4.2.2 (2) defines the design inter-storey drift (d_r) as the difference of the average lateral displacements (d_s) at the top and bottom of the storey under consideration.

According to clauses 4.4.3.1 and 4.4.3.2 of EN 1998-1:2004, the inter-storey drift (d_r) should be limited in order to verify the damage limitation requirement given by the following expression.

$$d_r \nu \leq (\propto).h$$

Where, reduction factor ν accounts for the lower return period to be considered in damage limitation requirement and it is 0.4 for the buildings of importance class III and IV and 0.5 for buildings of important class I and II (Clause 4.4.3.2 (2) of EN 1998-1:2001). The value of $\propto$ has three different figures, 0.005, 0.0075 and 0.01 depending on the type of non-structural elements in the building. The'h' is the height of the storey.

2.1.5.7 P-Δ effects

The clause 4.4.2.2 (2) of EN 1998-1:2004 recommends that P-Δ effects need not be taken into account if the value of inter storey drift sensitivity coefficient is less than 0.1. The inter storey drift sensitivity coefficient, θ is given by the expression below.

$\theta = \frac{P_{tot}.d_r}{V_{tot}.h} \leq 0.10$

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

For the values of inter-storey drift sensitivity coefficient between 0.1 and 0.2, the code advices to multiply the seismic action effects obtained from the analysis by a factor equal to 1/(1-θ). However, the inter-storey drift sensitivity coefficient shall not exceed 0.3.

2.2 Analysis procedure as described in Australian code (AS 1170.4-2007)

This section describes briefly the seismic analysis procedure, which has been established in the Australian code under different sub sections as follows.

2.2.1 Design seismic action

The structures shall be designed for a particular design working life (N), which defined as the minimum number of years for which a structure or a structural element is assumed in design to be used for its intended purpose with required maintenance but without major structural repair being necessary. This is a "reference period" according to AS/NZS 1170.0. it is a concept used to select the probability of exceedance of different actions.

For ultimate limit states for structures of importance levels 1 to 4, the annual probability of exceedance (P) for wind, snow and earthquake loads shall be determined as,

$$P = P_{ref} \times (50/N)$$

where,

P_{ref} = reference probability of exceedance for safety

N = design working life of the structure, in years

P = annual probability of exceedance

Table AS-1 :Reference probability of exceedance

Importance level	Annual probability of the design event for safety		
	Wind	Snow	Earthquake
1	1/100	1/50	1/100
2	1/500	1/150	1/500
3	1/1000	1/250	1/1000
4	1/2000	1/500	1/2500

Table AS-2 :Classification of buildings into important classes

Importance level	Comment	Examples
1	Structures presenting a low degree of hazard to life and other property	Farm buildings, isolated structures, towers in rural situations Fences, masts, walls, in-ground swimming pools
2	Normal structures and structures not in other importance levels	Hotels, offices, apartments less than 15 storeys high Car parking buildings Shopping centres less than 10,000m^2 gross area
3	Structures that as a whole may contain people in crowds or contents of high value to the community or pose risks to people in crowds	Emergency medical and other emergency facilities not designated as post-disaster Airport terminals, principal railway stations, correctional institutions, schools, colleges, universities Structures over 15 storeys high of the following types: (a)Hotels and motels (b) Apartment buildings (c) Offices Public assembly buildings of more than 1000m^2 Public museums and art galleries of more than 1000m^2 Shopping centres with covered malls with over 10000m^2 gross area excluding parking Grandstands for more than 10 000 people
4	Structures with special post-disaster functions	Major infrastructure facilities, e.g. power stations, substations Air traffic control stations Designated civilian emergency centres, medical emergency facilities, emergency vehicle garages and their fuel supplies and ambulance, fire and police stations, etc. Ancillary installations necessary for the operation of importance level 4 structures (emergency power, phone, radio, etc.) Medical facilities for surgery and emergency treatment, Hospitals, Fire and police stations, Ambulance facilities Buildings housing toxic or explosive substances in sufficient quantities to be dangerous to the public if released Extreme hazard facilities (Dams etc.)
5	Special structures (outside the scope of this Standard-acceptable probability of failure to be determined by special study)	Structures that have special functions or whose failure poses catastrophic risk to a large area(e.g. 100 $km^{2)}$ ora large number of people (e.g. 100 000) Dams, extreme hazard facilities

The structures shall be classified into five important classes (Table AS-2). The importance class 1 includes the structures, which does not require an explicit seismic consideration in the design process and also the domestic structures that comply with the definition given in appendix A and with the provisions of appendix A of the code are deemed to satisfy the standard. All other structures identified as important during an earthquake event considering their function, the consequences of failure and the economic aspects. Therefore, importance class 2, 3 and 4structures shall be designed for seismic actions having 500, 1000 and 2500 years return periods respectively.

The code AS 1170.4-2007 defines three earthquake design categories, category I, II and III

Table AS- 3 : Selection of earthquake design categories

Importance level, type of structure	(k_pZ) for site sub-soil class				Structure height, h_n (m)	Earthquake design category
	E_e or D_e	C_e	B_e	A_e		
1	-				-	Not required to be designed for earthquake actions
Domestic structure (housing)					Top of roof ≤8.5	Refer to Appendix A
					Top of roof >8.5	Design as importance level 2
2	≤0.05	≤0.08	≤0.11	≤0.14	≤12 >12, <50 ≥50	I II III
	>0.05 to ≤0.08	>0.08 to ≤0.12	>0.11 to ≤0.17	>0.14 to ≤0.21	<50 ≥50	II III
	>0.08	>0.12	>0.17	>0.21	<25 ≥25	II III
3	≤0.08	≤0.12	≤0.17	≤0.21	<50 ≥50	II III
	>0.08	>0.12	>0.17	>0.21	<25 ≥25	II III
4					<12 ≥12	II III

Where,

k_p : Probability factor (Refer Table AS-4)

z : Hazard factor (Table 3.2 of AS 1170.4 provides different values for "z" based on the location in Australia. However this can be taken as 0.1 for Sri Lanka)

Sub-soil classes have been defined in Clause 4.1.1 of AS 1170.4-2007 as,

(a) Class A_e- Strong rock

(b) Class B_e- Rock

(c) Class C_e- Shallow soil

(d) Class D_e- Deep or soft soil

(e) Class E_e- Very soft soil

However, in this analysis, only three soil conditions were considered B_e, C_e and E_e to represent Sri Lankan conditions, loose soil, medium soil and hard soil.

Table AS-4 :Probability factor k_p

Annual probability of exceedance *p*	**Probability factor** k_p
1/2500	1.8
1/2000	1.7
1/1500	1.5
1/1000	1.3
1/800	1.25
1/500	1.0
1/250	0.75
1/200	0.7
1/100	0.5
1/50	0.35
1/25	0.25
1/20	0.20

2.2.2 Horizontal elastic response spectra

AS 1170.4-2007 defines five different spectra under clause 6.4, based on site sub-soil classes.

Table AS-5 : Equations for spectra

T (seconds)	Equation for spectra				
	Ae Strong rock	**Be** Rock	**Ce** Shallow soil	**De** Deep or soft soil	**Ee** Very soft soil
$0<T\leq 0.1$	$0.8+15.5T$	$1.0+19.4T$	$1.3+23.8T$	$1.1+25.8T$	$1.1+25.8T$
$0.1<T\leq 1.5$	$0.704/T$ but ≤ 2.35	$0.88/T$ but ≤ 2.94	$1.25/T$ but ≤ 3.68	$1.98/T$ but ≤ 3.68	$3.08/T$ but ≤ 3.68
$T>1.5$	$1.056/T^2$	$1.32/T^2$	$1.874/T^2$	$2.97/T^2$	$4.62/T^2$

2.2.3 Vertical component of the seismic action

Clause 4.3.5.2 of EN 1998-1: 2004 states that If a_{vg} is greaterthan 0.25 g (2.5 m/s²) the vertical component of the seismic action should be taken into account in the cases listed below.

- For horizontal or nearly horizontal structures members spanning 20m or more;
- For horizontal or nearly horizontal cantilever components longer than 5m;
- For horizontal or nearly horizontal pre-stressed components;
- For beams supporting columns;
- In base-isolation systems;

It has been proposed to use recommendations provided in the Indian code, IS 1893 (Part 1):2002 for defining the vertical elastic spectra, which has been defined as 2/3 of the horizontal elastic spectra [5].

2.2.4 Seismic analysis of buildings

2.2.4.1 Seismic weight of the building

Clause 6.2.2 of AS1170.4-2007 states that seismic weight at each level which is taken into account in evaluating the inertial effects of the design seismic action is in the following combination of actions.

$$W_i = \sum G_i + \sum \psi_c \, . \, Q_{,i}$$

Where

Gi and $\psi_c Q_i$ are summed between the mid-heights of adjacent storeys

G_i = permanent action (self-weight or "dead load) at level i

ψ_c = earthquake-imposed action combination factor

$= 0.6$ for storage applications

$= 0.3$ for all other applications

Q_i= imposed action for each occupancy class on level i

2.2.4.2 Seismic Load Combination

The seismic load combination to be used in ultimate limit state used in checking strength has been given in Clause 4.2.2 of AS 1170.0-2007.

E_d =[G, Eu, $\psi_c Q$]

Where,

G : permanent actions (self-weight or"dead" action)

Eu :ultimate earthquake action

ψ_c : combination factor for imposed action

Q : imposed action

2.2.4.3 Structural Analysis

AS 1170.4-2007 describes two types of linear-elastic analysis as

I. Equivalent static analysis (Static)

II. Modal response spectrum analysis (Dynamic)

2.2.4.3.1 Equivalent Static Analysis

2.2.4.3.1.1 General

The procedure for equivalent static analysis is as follows:

(a) Decide on the form and material of the structure.

(b) Calculate $K_p Z$ using Section 3 of AS 1170.4-2007.

(c) Determine T_1, $C_h(T_1)$, $\mu$and other structural properties.

(d) Determine the design action coefficients.

(e) Determine the seismic weight at each level (W_i).

(f) Calculate V using Clause 6.2 of AS 1170.4-2007.

(g) Calculate F_i using Clause 6.3 of AS 1170.4-2007.

(h) Apply the forces to the structure at the eccentricities specified in Clause 6.6 of AS 1170.4-2007.

(i) Take P-delta effects into account as specified in Clause 6.7 of AS 1170.4-2007.

2.2.4.3.1.2 Horizontal equivalent Static forces

The set of equivalent static forces in the direction being considered shall be assumed to act simultaneously at each level of the structure and shall be applied taking into account the torsion effects as given in combination with other actions as specified in AS/NZS 1170.0. (Refer Clause 6.2.1 of AS 1170.4-2007)

The horizontal equivalent static shear force (V) acting at the base of the structure (base shear) in the direction being considered shall be calculated from the following equations

$V = C_d(T_1)W_t$ (Refer AS 1170.4-2007/eq 6.2(1))

$= [C(T_1)S_p/\mu]W_t$ (Refer AS 1170.4-2007/eq 6.2(2)

$= [K_pZC_h(T_1)S_p/\mu]W_t$ (Refer AS 1170.4-2007/eq 6.2(3))

Where

$C_d(T_1)$=horizontal design action coefficient (value of the horizontal design response spectrum at the fundamental natural period of the structure)

$=C(T_1)S_p/\mu$ (Refer AS 1170.4-2007/eq 6.2(4))

$C(T_1)$ = value of the elastic hazard spectrum

$=K_pZC_h(T_1)$(Refer AS 1170.4-2007/eq 6.2(5))

$C_h(T_1)$ = Value of the spectral shape factor for fundamental natural period of the structure, as given in Clause 6.4 of AS 1170.4- 2007.

W_t = Seismic weight of the structure taken as the sum of W_i for all levels, as given in Clause 6.2.2 of AS 1170.4-2007

S_p = Structural performance factor, as given in Clause 6.5 of AS 1170.4-2007.

μ = Structural ductility factor, as given in Clause 6.5 of AS 1170.4-2007.

T_1 = Fundamental natural period of the structure, as given in Clause 6.2.3 of AS 1170.4-2007 as,

$$T_1 = 1.25 k_t h_n^{0.75}$$

where,

k_t = 0.11 for moment-resisting steel frames

=0.075 for moment-resisting concrete frames

= 0.06 for eccentrically-braced steel frames

= 0.05 for all other structures

h_n =height from the base of the structure to the uppermost seismic weight or mass, in meters.

It should be noted that the base shear obtained using the fundamental structure period (T_1) determined by a rigorous structural analysis shall be not less than 80% of the value obtained with T_1 calculated using the above equation.

2.2.4.3.1.3 Vertical distribution of horizontal forces

The horizontal equivalent static design force (F_i) at each level (i) shall be obtained as (AS 1170.4-2007/eq. 6.3(1))

$$F_i = k_{F,i} V \qquad \text{(Ref AS 1170.4-2007/eq 6.3(1))}$$

$$= \frac{W_i h_i^{\,k}}{\sum_{j=1}^{n} W_j h_j^{\,k}} [K_p Z C_h(T_1) \frac{S_p}{\mu} /] W_t \quad \text{(Ref AS 1170.4- 2007/eq 6.2(2)}$$

Where

$k_{fi}(T_1)$=distribution factor for the i^{th} level

W_i =seismic weight of the structure at the i^{th} level, in kilonewtons

h_i =height of level i above the base of the structure, in metres

k=exponent depend on the fundamental period of the structure (T_1), which is taken as-

1.0 when $T_1 \leq 0.5$;

2.0 when $T_1 \geq 2.5$; or

linearly interpolated between 1.0 and 2.0 for $0.5 < T_1 < 2.5$

n=number of levels in a structure

The horizontal equivalent static earthquake shear force(V_i) at storey i is the sum of all the horizontal forces at and above the i^{th} level (F_i to F_n).

Table AS- 6 :Structural ductility factor (μ) and structural performance factor (S_p) - Basic structures

Structural	Description	μ	S_p	S_p/μ	μ/S_p
Steel Structures					
	Special moment-resisting frames (fully ductile) *	4	0.67	0.17	6
	Immediate moment-resisting frames (moderately ductile)	3	0.67	0.22	4.5
	Ordinary moment-resisting frames (limited ductile)	2	0.77	0.38	2.6
	Moderately ductile concentrically braced frames	3	0.67	0.22	4.5
	Limited ductile concentrically braced frames	2	0.77	0.38	2.6
	Fully ductile eccentrically braced frames *	4	0.67	0.17	6
	Other steel structures not defined above	2	0.77	0.38	2.6
Concrete structures					
	Special moment-resisting frames (fully ductile) *	4	0.67	0.17	6
	Immediate moment-resisting frames (moderately ductile)	3	0.67	0.22	4.5
	Ordinary moment-resisting frames	2	0.77	0.38	2.6
	Ductile coupled walls (Fully ductile) *	4	0.67	0.17	6
	Ductile partially coupled walls *	4	0.67	0.17	6
	Ductile shear walls	3	0.67	0.22	4.5
	Limited ductile shear walls	2	0.77	0.38	2.6
	Ordinary moment-resisting frames in combination with a limited	2	0.77	0.38	2.6
	Other concrete structures not listed above	2	0.77	0.38	2.6
Timber structures					
	Shear walls	3	0.67	0.22	4.5
	Braced frames (with ductile connections)	2	0.77	0.38	2.6
	Moment-resisting frames	2	0.77	0.38	2.6
	Other wood or gypsum based seismic-force-resisting systems not	2	0.77	0.38	2.6
Masonry structures					
	Close-spaced reinforced masonry †	2	0.77	0.38	2.6
	Wide-spaced reinforced masonry †	1.5	0.77	0.5	2
	Unreinforced masonry †	1.25	0.77	0.62	1.6
	Other masonry structures not complying with AS 3700	1	0.77	0.77	1.3

*The design of structures with μ>3 is outside the scope of this standard (Refer clause 2.2)

† These values are taken from AS 3700

2.2.4.3.1.4 Torsional effects

For earthquake action determined in each direction shall be applied at position calculated as ±0.1b from the nominal centre of mass, where b is the plan dimension of the structure at right angles to the direction of the action as described in clause 6.6 of AS 1170.4-2007.

This±0.1beccentricity shall be applied in the same direction at all levels and oriented to produce the most adverse torsion moment for the 100% and 30% loads.

2.2.4.3.1.5 Drift determination

Storey drifts shall be assessed for the two major axes of a structure considering horizontal earthquake forces acting independently, but not simultaneously, in each direction. The design drift (d_{st}) shall be calculated as the difference of the deflections (d_i) at the top and bottom of the storey under consideration.

$$d_i = d_{ie}\mu/S_p$$

Where,

d_{ie} : deflection at the i^{th} level determined by an elastic analysis carried out using the horizontal equivalent static earthquake forces (Fi).

2.2.4.3.1.6 *P*-delta effects

For the inter-storey stability coefficient (θ) calculated for each level, design for p-delta effects shall be as follows (Refer Clause 6.7.3.1 of AS 1170.4-2007),

(a) For $\theta \leq 0.1$, *P*-delta effects need not be considered.

(b) For $\theta > 0.2$, the structure is potentially unstable and shall be re-designed.

(c) For $0.1 < \theta \leq 0.2$, *P*-delta effects shall be calculated as described in Clause 6.7.3.2 of AS1170.4-2007.

$$\theta = d_{st} \sum_{j=1}^{n} W_j / \left(h_{si} \mu \sum_{j=1}^{n} F_j\right)$$

Where,

i = Level of the structure under consideration.

h_{si}= Inter-storey height of level i, measured from centre-line to centre-line of the floors.

.

When P-delta effects need to be considered, the values of the horizontal earthquake shear forces and moments, the resulting member forces and moments, and the storey drifts shall be determined by,

(a) scaling the equivalent static forces and deflections by the factor $(0.9/(1-\theta))\geq 1.0$ or.

(b) using a second-order analysis.

2.2.4.3.2 Modal response spectrum analysis

The earthquake ground motion shall be accounted for by using the method explained below either (a) or (b)

a) Horizontal design response spectrum ($C_d(T)$), including the side hazard spectrum and the effects of the structural response as follows (Refer AS 1170.4- 2007/7.2(a):

$C_d(T) = C(T)S_p/\mu$

$= K_p Z C_h(T) S_p/\mu$

Where,

T = period of vibration appropriate to the mode of vibration of the structure being considered

b) Site specific design response spectra developed for the specific site as described in Clause 7.2(b) of AS 1170.4-2007.

c) Where design includes consideration of vertical earthquake actions, both upwards and downwards directions shall be considered and the vertical design response spectrum shall be as follows (Refer Clause 7.2(3) of AS 1170.4-2007)

$$C_{vd}(T) = C_v(T_v)S_p$$

$$= 0.5C(T_v)S_p$$

$$= 0.5K_pZC_h(T_v)S_p$$

Where,

$C_v(T_v)$ = elastic site hazard spectrum for vertical loading for the vertical period of vibration

d) The response of all modes of vibration contribution significantly to the global response shall be considered. The code specifies that, this requirement is taken to be satisfied if.

- In two-dimensional analysis, sufficient modes shall be included in the analysis to ensure that at least 90% of the mass of the structure is participating for the direction under consideration.

- In three-dimensional analysis, where structures are modeled so that modes that are not those of the seismic-force-resisting system are considered, then all modes not part of the seismic-force-resisting system shall be ignored, Further, all modes with periods less than 5% of the fundamental natural period of the structure may be ignored.

e) AS 1170.4-2007 recommends the accidental torsional effects to be taken into account in the seismic analysis whenever a spatial model is used.

2.2.4.4 Earthquake design categories

Once the importance level, $k_{p,}$ Z, soil category and building height is known, the earthquake design category of the structure can be found referring to table AS-3.

2.2.4.4.1 Earthquake design category I (EDC I)

The structures can be designed by applying equivalent static forces applied laterally to the centre of mass at each level of the structure in combination with gravity loads[G, Eu, $\psi_c Q$] as given below (AS 1170.4-2007/eq 5.3),

$$F_i = 0.1 W_i$$

Where,

W_i = seismic weight of the structure at level i as given in Clause 6.2.2

a) Each of the major axes of the structure shall be considered separately.

b) Vertical earthquake actions and pounding need not be considered, except where vertical actions apply to parts and components.

2.2.4.4.2 Earthquake design category II (EDC II)

The structural system shall be designed to resist the most critical action effect arising from the application of the earthquake actions in any direction as given in Clause 5.4.2.1 of AS 1170.4-2007.

a) Except for structure components and footings that participate in resisting horizontal earthquake forces in both major axes of the structure, this provision shall be deemed to be satisfied by applying the horizontal forces in the direction of each of the major axes of the structure and considering the effect for each direction separately.

b) For structure components and footings that participate in resisting horizontal earthquake forces in both major axes of the structure, the effects of the two directions determined separately shall be added by taking 100% of the horizontal earthquake forces for one direction and 30% in the perpendicular direction.

c) Forces shall be applied at the centre of mass of each floor except where offset from the centre of mass is required for the consideration of torsion effects.

d) Earthquake forces shall be calculated using the equivalent static method for structures exceeding 15m.

e) For structures not exceeding 15m, the earthquake forces shall be calculated and applied according to Clause 5.4.2.3 of AS 1170.4-2007 and the minimum horizontal static force to be applied simultaneously at each level for the given direction is given by,

$$F_i = K_s[K_p Z S_p/\mu]W_i$$

Where,

K_p and Z are given in section 3 and S_p and μ are given in Clause 6.5 of AS 1170.4-2007

K_s = Factor to account for floor, as given in table 5.4 of AS 1170.4-2007

W_i = Seismic weight of the structure or component at level i

Table AS-7 :Value of K_s for structures not exceeding 15m

Total number of stories	Sub-soil class	K_s factor				
		Storey under consideration				
		5th	4th	3rd	2nd	1st
5	A_e	2.5	1.9	1.4	1.0	0.5
	B_e	3.1	2.5	1.8	1.2	0.6
	C_e	4.4	3.5	2.6	1.7	0.9
	D_e , E_e	6.1	4.9	3.6	2.5	1.2
4	A_e		2.7	2.0	1.4	0.6
	B_e		3.5	2.6	1.7	0.9
	C_e		4.9	3.6	2.5	1.2
	D_e , E_e		5.8	4.4	3.0	1.4
3	A_e			3.1	2.0	1.0
	B_e			3.9	2.6	1.3
	C_e , D_e , E_e			5.5	3.6	1.8
2	A_e				3.1	1.6
	B_e				3.9	1.9
	C_e , D_e , E_e				4.9	2.5
1	A_e					2.3
	B_e					3.0
	C_e , D_e , E_e					3.6

a) Alternatively, dynamic analysis shall be used to find out design earthquake actions according to Section 7 of AS 1170.4-2007.

b) Vertical earthquake actions need not be considered. For parts and components refer Clause 5.4.6 and 8.1.3 of AS 1170.4-2007.

c) The inter-storey drift at the ultimate limit state shall not exceed1.5% of the storey height of each level (Refer Clause 5.4.4 of AS 1170.4-2007).

2.2.4.4.3 Earthquake design category III (EDC III)

The structural system shall be designed to resist the most critical action effect arising from the application of the earthquake actions in any direction as given in Clause 5.5.2.1 of AS 1170.4-2007.

a) Except for structure components and footings that participate in resisting horizontal earthquake forces in both major axes of the structure, this provision shall be deemed to be satisfied by applying the horizontal forces in the direction of each of the major axes of the structure and considering the effect for each direction separately.

b) For structure components and footings that participate in resisting horizontal earthquake forces in both major axes of the structure, the effects of the two directions determined separately shall be added by taking 100% of the horizontal earthquake forces for one direction and 30% in the perpendicular direction.

c) Earthquake forces shall be calculated using the dynamic analysis method given in Section 7 of AS 1170.4-2007.

d) Vertical earthquake actions need not be considered. For parts and components, refer Clause 8.1.3 of AS 1170.4-2007.

e) The inter-storey drift at the ultimate limit state shall not exceed1.5% of the storey height of each level (Refer Clause 5.5.4 of AS 1170.4-2007).

2.3 Analysis procedure as described in Indian code [IS 1893 (Part 1) : 2002]

The design approach adopted in this standard is to ensure that structures possess at least a minimum strength to withstand minor earthquakes (<Design Based Earthquake, DBE), which occurs frequently, without damages; resist moderate earthquakes (DBE) without significant structural damage though some non-structural damage may occur; and aims that structures withstand a major earthquake (Maximum Considered Earthquake, MCE) without collapse.

2.3.1 Horizontal elastic response spectra

The IS 1893 (Part 1) : 2002 has defined the spectra, $\frac{S_a}{g}$ for 5 percent damping to be used in seismic analysis as follows.

$$0.00 \leq T \leq T_B \quad \frac{S_a}{g} = 1 + 15T$$

$$T_B \leq T \leq T_C \quad \frac{S_a}{g} = 2.5$$

$$T_C \leq T \leq 4.00 \quad \frac{S_a}{g} = S/T$$

Where

$\frac{Sa}{g}$	: 5 percent spectra
T	: natural period of the structure
T_B	: lower limit of the period of the constant spectral acceleration branch
T_C	: upper limit of the period of the constant spectral acceleration branch
S	: soil factor

The horizontal elastic response spectra are given for three types of soil classified based on the Standard Penetration Test value (N_{SPT}). For the soil classification and the corresponding parameters defining the elastic response spectra see Table 3.

Table IS-1: Soil classification and parameters defining horizontal elastic response spectra

Soil Type	N_{SPT}	S	T_B	T_C
I	>30	1	0.1	0.4
II	10-30	1.36	0.1	0.55
III	<10	1.67	0.1	0.67

2.3.2 Vertical component of the seismic action

Vertical acceleration shall be considered in structures as described in Clause 6.1.1 of IS 1893 (Part 1) : 2002, for structures with large spans, those in which stability is a criterion for design, or for overall stability analysis of structures. Reduction in gravity force due to vertical component of ground motions can be particularly detrimental in cases of pre-stressed horizontal members and of cantilevered members.

The design acceleration spectrum vertical motions, when require, may be taken as two-thirds of the design horizontal acceleration spectrum (See Clause 6.4.5 of IS 1893 (Part 1) : 2002).

2.3.3 Design horizontal seismic coefficient

The design horizontal seismic coefficient, A_h has been defined in IS 1893 (Part 1) : 2002 as follows,

$$A_h = \frac{ZIS_a}{2Rg}$$

Where

Z : Zone factor given in table 2 of IS 1893 (Part 1) : 2002, is for the Maximum considered Earthquake(MCE) and service life of structure in a zone. The factor 2 in the denominator of Z is used so as to reduce the maximum Considered Earthquake (MCE) zone factor to the factor for Design Basis Earthquake (DBE).

I : Importance factor, as defined in table 6 of IS 1893 (Part 1) : 2002, depending upon the functional use of the structures, characterized by hazardous consequences of its failure, post-earthquake functional needs, historical value, or economic importance.

R : Response reduction factor, as defined in table 7 of IS 1893 (Part 1) : 2002, depending on the perceived seismic damage performance of the structure, characterized by ductile or brittle deformations. However, the ratio (I/R) shall not be greater than 1.0

$\frac{S_a}{g}$: Average response acceleration coefficient.

Table IS-2 :Zone factor, Z (Table 2 of IS 1893 (Part 1) : 2002)

Seismic Zone	**II**	**III**	**IV**	**V**
Seismic Intensity	Low	Moderate	Severe	Very Severe
Z	0.10	0.16	0.24	0.36

Table IS-3 : Importance Factor, I (Table 6 of IS 1893 (Part 1) : 2002)

SI No.	**Structure**	**Importance Factor**
i)	Important service and community buildings, such as hospitals; schools; monumental structures; emergency buildings like telephone exchange, television stations, radio stations, railway stations, fire station buildings; large community halls like cinemas, assembly halls and subway stations, power stations	1.5
ii)	All other buildings	1.0

Notes:

1. The design engineer may choose values of importance factor I greater than those mentioned above.
2. Buildings not covered in SI No. (i) and (ii) above may be designed for higher value of I, depending on economy, strategy considerations like multi-storey buildings having several residential units.
3. This does not apply to temporary structures.

Table IS-4 : Response reduction factor[1)], R (Table 7 of IS 1893 (Part 1) : 2002)

SI No.	Lateral load resisting system	*R*
	Building Frame Systems	
i)	Ordinary RC moment-resisting frame (OMRF)[2)]	3.0
ii)	Special RC moment-resisting frame (SMRF)3[)]	5.0
iii)	Steel frame with	
	a) Concentric braces	4.0
	b) Eccentric braces	5.0
iv)	Steel moment-resisting frame designed as per SP 6 (6)	5.0
	Building with Shear Walls[4)]	
v)	Load bearing masonry wall buildings[5)]	
	a) Unreinforced	1.5
	b) Reinforced with horizontal RC bands	2.5
	c) Reinforced with horizontal RC bands and vertical bars at corners of rooms and jambs of openings.	3.0
vi)	Ordinary reinforced concrete shear walls[6)]	3.0
vii)	Ductile shear walls[7)]	4.0
	Building with Dual Systems[8)]	
viii)	Ordinary shear wall with OMRF	3.0
ix)	Ordinary shear wall with SMRF	4.0
x)	Ductile shear wall with OMRF	4.5
xi)	Ductile shear wall with SMRF	5.0

(Note: Refer Table 7of IS 1893 (Part 1) : 2002 for full details, which are described by superscripts 1 to 8)

*) Buildings with shear walls also include buildings having shear walls and frames, but where;

a) frames are not designed to carry lateral loads, or

b) frames are designed to carry lateral loads but do not fulfill the requirements of ' dual systems '.

*) Buildings with dual systems consist of shear walls (or braced frames) and moment resisting frames such that;

a) the two systems are designed to resist the total design force in proportion to their lateral stiffness considering the interaction of the dual system at all floor levels; and

b) the moment resisting frames are designed to independently resist at least 25 percent of the design seismic base shear.

2.3.4 Seismic analysis of buildings

2.3.4.1 Seismic weight of the building

The seismic weight of a building shall be calculated as per Clause 7.43 of IS 1893 (Part 1) : 2002. The seismic weight of the whole building is the sum of the seismic weights of all the floors. The seismic weight of each floor is its full dead load plus an appropriate amount of imposed loads as given in table 8 of IS 1893 (Part 1) : 2002.

Table IS-5 :Percentage of imposed load to be considered in seismic weight calculation in (Table 8 of IS 1893 (Part 1) : 2002)

Imposed uniformity distributed floor loads (kN/ m^2)	Percentage of imposed load
Upto and including 3.0	25
Above 3.0	50

2.3.4.2 Structural Irregularity

A buildings shall be categorized as irregular, if atleast one of the conditions described in table 4 and 5 of IS 1893-1:2002are applicable (Refer Clause 7.1 of IS 1893 (Part 1) : 2002).

2.3.4.2.1 Plan irregularity

A building shall be considered as irregular in plan, if atleast one of the conditions described below is applicable (Refer Table 4 of IS 1893 (Part 1) : 2002).

- Torsional irregularity:

  Torsional irregularity to be considered to exist when the maximum storey drift, computed with design eccentricity, at one end of the structures transverse to an axis is more than 1.2 times the average of the storey drifts at the two ends of the structure.

- Re-entrant corners:

  Plan configuration of a structure and its lateral force resisting system contain re-entrant corners, where both projections of the structure beyond the re-entrant corner are greater than 15 percent of its plan dimension in the given direction.

- Diaphragm discontinuity:

  Diaphragm with abrupt discontinuities or variations in stiffness, including those having cut-out or open areas greater than 50percent of the gross enclosed diaphragm area, or changes in effective diaphragm stiffness of more than 50 percent from one storey to the next.

- Out-of-Plane Offsets:

  Discontinuities in a lateral force resistance path, such as out-of-plane offsets of vertical elements.

- Non-parallel System:

  The vertical elements resisting the lateral force are not parallel to or symmetric about the major orthogonal axes or the lateral force resisting elements.

2.3.4.2.2 Vertical irregularity

A building shall be considered as vertically irregular, if atleast one of the conditions described below is applicable (Refer Table 5 of IS 1893 (Part 1) : 2002).

- Stiffness irregularity:

  (a) Soft storey:

  A soft storey is one in which the lateral stiffness is less than 70 percent of that in the storey above or less than 80 percent of the average lateral stiffness of the three storeys above.

  (b) Extreme soft storey:

  An extreme soft storey is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70 percent of the average stiffness of the three storeys above.

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- Mass irregularity:

  Mass irregularity shall be considered to exist where the seismic weight of any storey is more than 200 percent of that of its adjacent storeys. The irregularity need not be considered case of.

- Vertical geometric irregularity:

  Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral force resisting system in any storey is more than 150 percent of that in its adjacent storey.

- In-Plane Discontinuity in vertical elements resisting lateral force:

  A in-plane offset of the lateral force resisting elements greater than the length of those elements.

- Discontinuity in capacity - Weak storey:

  A weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above.

2.3.4.3 Structural Analysis

IS 1893 (Part 1) : 2002 describes two types of linear-elastic analysis as

I. Lateral force method of analysis (Static)

II. Modal response spectrum analysis (Dynamic)

a) The use of above two methods of analysis shall be decided based on the structural characteristics of the building.

b) For the consequences of structural regularity on the structural analysis method, refer Table IS-6 (Clause 7.8.1of IS 1893 (Part 1) : 2002)

Table IS-6 :Consequences of structural regularity on structural model and the analysis method

Regularity	Building Height (m)	Zone	Analysis method
Regular	>40m	IV, V	Dynamic Analysis
	>90m	II, III	Dynamic Analysis
	All other buildings		Lateral Force Method
Irregular	>12m	IV, V	Dynamic Analysis
	>40m	II, III	Dynamic Analysis
	All other buildings		Lateral Force Method

Note-

For irregular buildings, lesser than 40min height in zones II and III, dynamic analysis, even though not mandatory, is recommended in IS 1893 (Part 1) :2002.

2.3.4.3.1 Static lateral force method of analysis

The total design lateral force or design seismic base shear (V_B) along any principal direction shall be determined by the following expression (Refer Clause 7.5.3 of IS 1893 (Part 1) : 2002).

$$V_B = A_h W$$

Where

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration.

W: Seismic weight of the building.

2.3.4.3.1.1 Fundamental natural period

The approximate fundamental natural period of vibration (T_a), in seconds for different types of buildings have been defined as follows (Refer Clause 7.6.1 of IS 1893 (Part 1) : 2002);

- For a moment-resisting frame building without brick infill panels may be estimated as,

  $T_a = 0.075\, h^{0.75}$ for RC frame building

  $= 0.085\, h^{0.75}$ for steel frame building and

- For all other buildings,

  $$Ta = \frac{0.09h}{\sqrt{d}}$$

Where,

h = Height of the building, in m and

d = Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force.

2.3.4.3.1.2 Distribution of design force

The design base shear (V_B) shall be distributed along the height of the building as per the following expression (Refer Clause 7.7.1 of IS 1893 (Part 1) : 2002);

$$Q_i = V_B \frac{w_i}{\sum_{j=1}^{n} w_j h_j^2} h_i^2$$

Where

Q_i: Design lateral force at floor *i*,

W: Seismic weight of the floor *i* ,

h_i: Height of floor i measured from base ,

n: Number of storeys in the building is the number of levels at which the masses are located.

2.3.4.3.2 Dynamic analysis - Response spectrum method

This type of analysis is generally recommended to use for any building. The following are the important aspects that should be considered in the analysis procedure in accordance with the code.

a) When the design base shear (V_B), obtained by response spectrum analysis is lesser than the base shear ($\overline{V_B}$), calculated using a fundamental period Ta, where Ta is as per section 7.6 of IS 1893 (Part 1) : 2002, all the response quantities shall be multiplied by $\overline{V_B}/V_B$.

b) The number of modes to be used in the analysis should be such that the sum total of modal masses of all modes considered is at least 90 percent of the total seismic mass correction beyond 33 percent. If modes with natural frequency beyond 33HZ are to be considered, modal combination shall be carried out only for modes up to 33HZ. The effect of higher modes shall be included by considering missing mass correction following well established procedures (Refer Clause 7.8.4.2 of IS 1893 (Part 1) : 2002).

c) Combination of modal responses is an important step in the modal response spectrum analysis. The Clause 7.8.4.4 of IS 1893 (Part 1) : 2002 recommends the "Complete Quadratic Combination" (CQC) rule as an accurate procedure for this. For buildings with regular or normally irregular plan configurations, the code IS 1893-1:2002allows to use a model as a system of masses lumped at the floor levels with each mass having one degree of freedom, that of lateral displacement in the direction under consideration(Refer Clause 7.8.4.5 of IS 1893 (Part 1) : 2002).

d) IS 1893 (Part 1) : 2002 recommends the accidental torsional effects to be taken into account in the seismic analysis whenever a spatial model is used.

2.3.4.4 Torsional effects

Provision shall be made in all buildings for increase in shear forces on the lateral force resisting elements resulting from the horizontal torsional moment arising due to eccentricity between the centre of mass and centre of rigidity as described in Clause 7.9 of IS 1893 (Part 1) : 2002. The design forces calculated are to be applied at the centre of mass appropriately displaced so as to cause design eccentricity between the displace centre of mass and centre of rigidity. However, negative torsional shear shall be neglected.

The design eccentricity, e_{di} to be used at floor i shall be taken as:

$e_{di} = \{1.5\ e_{si} + 0.05\ b_i\}$

or $\{e_{si} - 0.05\ b_i\}$

whichever of these gives the more severe affect in the shear of any frame where,

e_{si} = Static eccentricity at floor i defined as the distance between centre of mass and centre of rigidity.

b_i = Floor plan dimension of floor i, perpendicular to the direction of force.

2.3.4.5 Storey drift limitation

The storey drifts in any storey due to the minimum specified design lateral force, with partial safety factor of 1.0, shall not exceed 0.004 times the storey height (Refer Clause 7.11.1of IS 1893 (Part 1) : 2002).

For the purpose of displacement requirements only, it is permissible to use seismic force obtained from the computed fundamental period (T) of the building without the lower bound limit on design seismic force specified in Clause 7.8.2 of IS 1893 (Part 1) : 2002.

There shall be no drift limit for single storey building which has been designed to accommodate storey drift.

2.4Comparison of analysis procedures as described in the Euro code, the Australian code and the Indian code

The sections 2.1, 2.2 and 2.3 have demonstrated the analysis procedures, which have been described the Euro code, the Australian code and the Indian code respectively. This section has been used to discuss and compare the analysis procedures, which have been described in those codes of practice, the advantages and disadvantages between them, how those codes have defined different parameters and their proposed values for them and how those codes have considered different structural effects in their analysis etc.

2.4.1 Sub-soil conditions

In defining the elastic response spectra, the Euro code and the Australian code have defined it for five sub-soil conditions whereas the Indian code has defined the spectra only for three sub-soil conditions.

The sub-soil types, defined in the Indian code seems to be more convenient to be applied in Sri Lankan conditions, basically because of its simplicity in defining the sub-soil categories, which does not require sophisticated soil tests in doing so.

2.4.2 Structural regularity

For the purpose of seismic design, building structures are categorized into being regular or non-regular. However, the regularity has been considered in seismic design process by different codes of practice in different ways.

The Australian code has considered all the buildings to be irregular since, the most of the buildings in Australia are irregular.

The Indian code seems to address the irregularities by just requiring dynamic analysis.

However, the Euro code has considered the effect of a building being irregular in many ways. In instance, the code recommends to use a reduced value for basic behavior factor, $q_0$for buildings, which are not regular in elevation.

2.4.3 Seismic hazard factor

According to the Euro code and the Australian codes of practice, the design seismic actions have to be evaluated based upon Maximum Considered Earthquake (MCE), whereas the Indian code recommends to use a reduced zone factor ($Z/2$) in evaluating seismic actions representing the Design Base Earthquake (DBE) situation, which consequently gives lower response values compared to two other codes of practice.

2.4.4 Design base shear force

Design base shear force can be determined either by static method or dynamic method of analysis, according to three of the codes considered. As per the Euro code and the Australian code, the design base shear forces can be determined by two of above methods independently. However, the Indian code has defined a lower bound value for design base shear force. As per the Indian code, when the design base shear (V_{B}), obtained by response spectrum analysis is lesser than the base shear ($\overline{V_{\mathrm{B}}}$), calculated using static method of analysis, then all the response quantities shall be multiplied by $\overline{V_{\mathrm{B}}}/V_{\mathrm{B}}$.

2.4.5 Accidental Torsional effect

In order to account for accidental torsional effect, the Euro code and the Indian code recommend to apply the earthquake loads at a position 0.05b from the nominal centre of mass whereas the Australian code recommends 0.1b from the nominal centre of mass, where b is the plan dimension of the structure at right angle to the direction of action.

2.4.6 *P*-delta effects

The Euro code and the Australian code have described the way to determine the *P*-delta effects in calculation based upon θ, the inter-storey sensitivity coefficient, according to the Euro code and the inter-storey stability coefficient, according to the Australian code. However, the Indian code does not provide such a method to determine the *P*-delta effects in seismic design calculation.

2.5 Review over previous research studies

When going through the literature, it has been found that a number of researches have been carried out in the similar area of study in different parts of the world. This section briefly presents some of those important studies, explaining the objectives, the methodology they have adopted and major findings through the results obtained etc.

In their research, **Yogendra Singh [15]** intended to compare the code provisions for seismic analysis and design of ductile RC frame buildings. All current seismic design codes are based on a prescriptive Forced-Based Design approach. In this approach, a linear elastic analysis is performed and inelastic energy dissipation is considered indirectly through a response reduction factor (or a behavior factor). Building codes define different ductile classes and specify different response reduction factors based on the material, configuration and detailing. Codes also differ specifying the effective stiffness of RC members, procedures to estimate drift and allowable limits on drift. This research paper presents a comparative study of different ductility classes and corresponding response reduction factors, reinforcement detailing provisions and a case study of seismic performance of a ductile RC frame building designed using four major codes ASCE7 (United States), EN 1998-1 (Euro), NZS 1170.5 (New Zealand) and IS 1893 (India)

Based upon the results, as a conclusion, it states that the comparison of broad ductility classes suggests significant variation in different codes. It also conclude that, it is not possible to directly compare the response reduction factors for various ductility classes due to the variation in provisions for reinforcement detailing and capacity design provisions. It further states that the most of codes combine the effect of overstrength and ductility in a single reduction factor, except for NZS 1170.5, which considers the overstrength separately through a "structural performance factor".

This study also confirms that NZS 1170.5 results in the highest design base shear for a given period, for almost all the cases considered in the study. The design base shear as per Euro code 8 has become close to that of NZS 1170.5, while IS 1893 has resulted in lowest design base shear force for a given hazard. Based upon the seismic performance of an eight storied RC frame building, it has been noted that the inter storey drift ratio was greater than 2.5% for DBE and, equal or greater 4% for MCE for most of the codes.

Pravin Ashok Shirule [14] has performed a parametric study on reinforced concrete structural walls and moment resisting frame building representative of structural types, using response spectrum method. The objective of this project was to investigate the differences caused by the use of different codes in the dynamic analysis of multistoried RC building. Here, the design spectra recommended by Indian Standard Code, IS 1893 (Part a) : 2002 and two other codes, namely the Uniform Building Code and the Euro Code8 have been considered for comparison.

To evaluate the seismic response of the buildings, elastic analysis has been performed by using response spectrum method using the computer software SAP2000. Through this study, it has concluded that the base shear using Indian code is higher in all the three buildings, when compared to that of with other codes, which lead to overestimate the overturning moments in the building.

The study further concludes that for the buildings, UBC code gives the maximum and IS gives the minimum displacement values.

In another research, **Surabhi A [17]**has studied various researches, previously done by others, which give more information about the static and dynamic analysis done on various types of structures using various codes of practice to evaluate the seismic performance of those structures. The parameters such as displacement, base shear, storey drift, time period, axial and shear force and bending moment were studied. This work aimed at the comparison of various provisions for earthquake analysis as given in Indian code, American code, European code and in New Zealand code. In all the cases, computer modeling and response spectrum analysis have been done with the help of ETABS-2015 software.

Based on analysis, it concludes that the buildings designed using Euro code perform better comparing to the Indian code and the American code. It further suggests the requirement of improvements for Indian and American codes in performance based design.

In the research conducted by **Mehul J. Bhavsar [18]**, a comparative study has been done based upon a seismic analysis performed for a RC building according to Indian standard and Euro standard. The paper highlights the importance of doing such a study, because there is a possibility that the International Standards may have more parameters that are not included in Indian Standards. It further mention the importance of Euro code in developing country like India, because most of the Gulf countries, which are having remarkable infrastructures also follow Euro code.

In making the comparison, it has considered most of important criteria such as response reduction factor, ductility classes, maximum storey displacements, drift limitations, base shear, reactions and axial loads etc.

The paper concludes that the design base shear force obtained with IS 1893 was lower than the design base shear force calculated using the Euro code, because of the high response reduction factor, which has been used in analysis with Indian code.

3.0 METHODOLOGY

As described in the introduction chapter, firstly three main seismic analysis codes that are often used by Sri Lankan engineers were identified, namely the Euro code, EC-8 (EN 1998-1:2004), the Australian code (AS 1170.4-2007) and the Indian code (IS 1893 (Part 1):2002). In literature review section, the analysis procedures that have been established in each of those codes were outlined in step by step, discussing the important parameters and how they are to be used in Sri Lankan conditions etc.

Since these codes have established their own analysis procedures and parameters irrespective of other codes, it was very important to make a detail discussion over their analysis procedures, how those codes have defined different parameters and their proposed values and how those codes have considered different structural effects in their analysis etc. The latter parts of the literature review chapter has been used for this purpose.

The next task was to demonstrate through case studies how to apply the static and dynamic seismic analysis procedures described in those codes to analyse buildings in Sri Lanka under different geotechnical considerations. In order to achieve this objective, three different reinforced concrete building structures were selected for analysis namely, building "A", an eighteen storied residential apartment building, building "B", a fourteen storied residential apartment building and building "C", a ten storied residential apartment building.

Since it better represents the actual behavior of the structure, three dimensional computer models of those buildings were developed with elements of actual sizes, according to the guidelines provided in relevant sections of the particular codes of practice. For all the modeling and analysis purposes, computer software "ETABS" version 9.7 has been used.

The structures were then dynamically analysed for seismic effects as described in the respective codes of practice. Response Spectrum Analysis (RSA) was used for all dynamic analysis purposes. Equivalent static analysis were also done as per requirements, established in particular codes of practice.

In order the results to be more general, all of the above three buildings were analysed for three different soil conditions, which can be commonly found in Sri Lanka, namely soft soil, medium soil and hard soil. In this way, a total of twenty seven cases were studied. A detail description of the analysis procedures have been presented in the respective sections of the analysis chapter

Finally the output results, like drifts and base shear forces obtained under different codes and soil conditions were studied to find out how they vary when moving between different soil conditions and different codes of practice, which helped in making final conclusion of the research.

4.0 ANALYSIS ACCORDING TO EURO CODE { EN 1998-1:2004}

4.1 BUILDING "A"

4.1.1 Design seismic action

Classification of building

Since this is an apartment building having more than 10 storeys, the structure is categorized as importance level III (*Table EN1*)

Design peak ground acceleration

Since $a_{g,475} = 0.1g$ (*Table EN-2)* and

$\gamma_1 = 1.5$ (*Table EN-2)*

The design peak ground acceleration value was then calculated as

$a_g = (0.1g \times 1.5) = 0.15g$

Behavior factor (q)

This building has been designed for Ductility Class Medium (DCM) conditions. The behavior factor, q for this building, according to Clause 5.2.2.2 of EN 1998-1:2004,

$q = q_0 k_w$

The structural type of the building has been considered as torsionally flexible system. The q_0 for a torsionally flexible system, which is regular in elevation is given as,

$q_0 = 2.0$ (*Table EN-4*)

Since the selected building is irregular in elevation, 80% of the q_0 has to be used in calculations, as described in appendix A-2.1.2.

For a torsionally flexible system,

$k_w = (1 + \alpha_0)/3 \leq 1$, but not less than 0.5 (*Table EN-5*)

And,

$$\propto_0 = \sum h_{wi} / \sum l_{wi}$$

$\propto_0$=9.96

Therefore,

k_w= (1+9.96)/3

Therefore, k_w can be taken as 1.0

Therefore,

q = (0.8×2× 1) = 1.6

Elastic response spectrum and design response spectrum for three different types of soil conditions and are shown in figure EA-1.

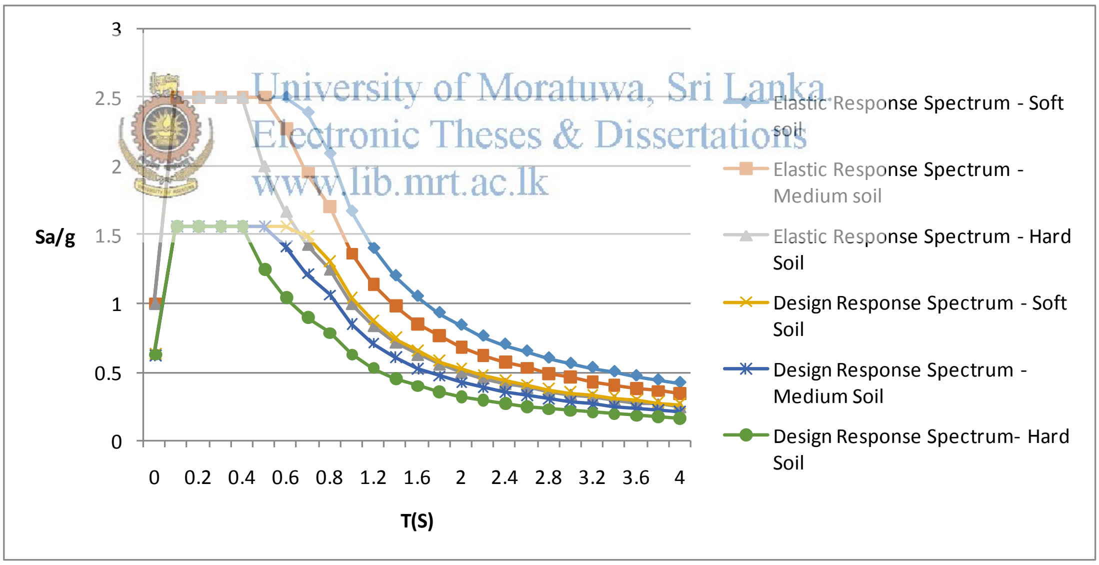

Figure EA-1 : Elastic response spectrum and design response spectrum - Building A

4.1.2 Methods of analysis

A modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis was also performed in order to obtain the horizontal force acting on each storey, which was used to determine accidental torsional effects as described in section 2.1.5.5.

All the computer analysis were performed with the ETABs software (CSI 2002. ETABS Integrated Building Design Software, Computers and Structures Inc. Berkley).

4.1.2.1Structural Model

The *EN 1998-1:2004* recommends using a spatial model as the preference method for all type of buildings(*Clause 4.3.1of EN 1998-1:2004*). On account of that, for the test building a three dimensional (spatial) model was developed.

In this study, the building has been considered to have no significant structural effect from the masonry infill walls on its behavior when subjected to seismic load. The reinforced concrete frame wall system was considered as the only lateral load resisting system in the building and therefore, the presence of masonry infill walls were neglected in the model. However, their weight was considered in the calculation of seismic weight of the building.

It is required that the model should fulfill all the requirements specified in the code. The basic characteristics of the model of the test building considering the requirements in the code are as follows.

- Column and beam elements were modeled as line elements whereas the floor slabs and concrete walls were modeled as shell elements.
- Unreinforced masonry infill walls were not included in the model assuming that they have no contribution to the stiffness or the lateral strength of the building, but the weight of those walls were applied to the model.
- The elements were modeled with the actual sizes such that they adequately represent the distribution of stiffness and mass of the building.
- The cracked elements were considered in the analysis according to Clause 4.3.1(6) of EN 1998-1: 2004**.**The elastic flexural and shear properties of the cracked sections were taken to be equal to one-half of the

corresponding stiffness of the un-cracked elements (EN 1998-1: 2004/4.3.1 (7)).

- Torsional stiffness of the cracked section was set equal to 10% of the torsional stiffness of the un-cracked section.
- Frames were connected by means of rigid diaphragms in horizontal plane at each floor level.
- The accidental torsional effects were considered by applying torsional moments about vertical axis.

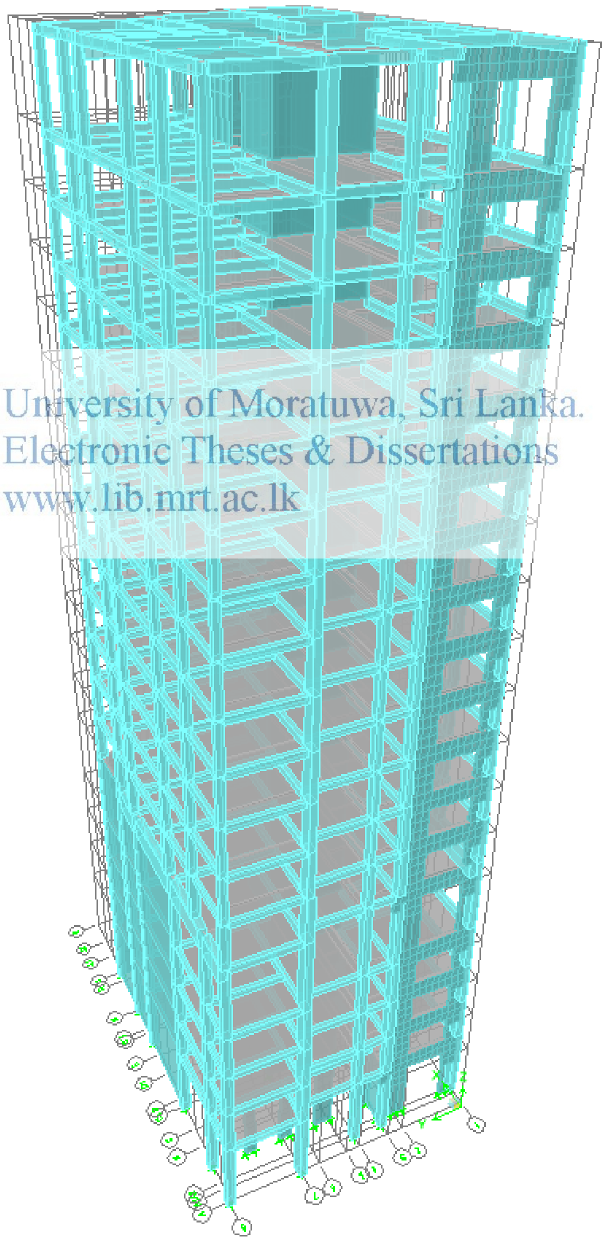

Figure EA-2 : Three dimensional (spatial) model of Building A

4.1.2.2 Lateral force method of analysis

The lateral force method of analysis has been carried out in three main steps as follows.

a) Estimating the self-weight and seismic masses of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces and moments

4.1.2.2.1 Estimation of seismic mass of the building

As described in section 2.1.5.1, the seismic mass of the building was taken as the following combination of dead load and the variable loads as,

$$\sum G_{k,j} + \sum \psi_{E,i} Q_{k,I}$$

Table EA-1 : Total seismic mass of building A

Storey	ψ_2 (Table EN-7)	ψ (Table EN-9)	$G_{k,j}$ (t) (Table A-3)	$Q_{k,I}$ (t) (Table A-4)	Seismic mass (t)	Total Seismic mass (t)
Roof	0	1	492	82	492	492
Storey 17	0.3	0.8	634	82	654	654
Storey 7-16	0.3	0.8	596	82	616	6160
Storey 6	0.3	0.8	604	82	624	624
Storey 5	0.3	0.8	766	82	786	786
Storey 4	0.6	0.5	628	123	665	665
Storey 3-2	0.6	0.5	562	123	599	1198
Storey 1	0.6	0.5	638	123	675	675
Total seismic mass of the building						11,254

4.1.2.2.2 Calculation of seismic base shear

As described in section 2.1.5.4.1, the seismic base shear force for each horizontal direction was determined by the following equation,

$$F_b = S_d(T_1).m.\lambda$$

where,

T_1: The fundamental period of the building – Refer table A5

$S_d(T_1)$: The value of the ordinate of the design response spectrum, corresponding to the fundamental period T_1 of the building for different soil conditions – Refer figure EA-1

m: The seismic mass of the building - Refer table EA-1

λ : The correction factor, λ can be determined according to clause 4.3.3.2.2 of EN 1998-1: 2004.

The values of λ for three different soil conditions are shown in table EA-2.

The base shear forces for each horizontal direction, F_b for three soil conditions are shown in Table EA-3.

Table EA-2: Correction factor, λ for building A

Soil Type	T_c	$2T_c$	T_x	T_y	λ_x	λ_y
Soft	0.67	1.34	1.32	1.64	0.85	1.00
Medium	0.55	1.10	1.32	1.64	1.00	1.00
Hard	0.40	0.80	1.32	1.64	1.00	1.00

Table EA-3:Seismic base shear of building A

Soil Type	Fundamental Period, T_1 (S)		$S_d(T_1)$		m (t)	λ		F_b(kN)	
	X	Y	X	Y		X	Y	X	Y
Soft	1.32	1.64	1.1772	0.9432	11,254	0.85	1.00	11261	10615
Medium	1.32	1.64	0.9609	0.9432	11,254	1.00	1.00	10814	8612
Hard	1.32	1.64	0.7063	0.568	11,254	1.00	1.00	7949	6392

4.1.2.2.3 Distribution of lateral forces

The seismic base shear (F_b) was distributed at each storey level by using the following expression as shown in section 2.1.5.4.1(C),

$$F_i = F_b . \frac{z_i . m_i}{\sum z_j . m_j}$$

The distribution of seismic base shear at each storey level is shown in Table EA-4.

Table EA-4 :Distribution of seismic base shear at each storey level - Building A

Storey	Height (z_i) (m)	Mass (m_i) (t)	$Z_i.m_i$ (tm)	Fi(kN)					
				Soft		Medium		Hard	
				F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}
Roof	71.2	492	35031	925	872	888	707	653	525
Storey 17	66	654	43164	1140	1074	1094	872	804	647
Storey 16	62.4	616	38439	1015	957	975	776	716	576
Storey 15	58.8	616	36221	956	901	918	731	675	543
Storey 14	55.2	624	34445	909	857	873	696	642	516
Storey 13	51.6	616	31786	839	791	806	642	592	476
Storey 12	48	616	29568	781	736	750	597	551	443
Storey 11	44.4	616	27351	722	681	693	552	510	410
Storey 10	40.8	616	25133	664	626	637	507	468	377
Storey 9	37.2	616	22916	605	570	581	463	427	343
Storey 8	33.6	616	20698	546	515	525	418	386	310
Storey 7	30	616	18480	488	460	469	373	344	277
Storey 6	26.4	624	16474	435	410	418	333	307	247
Storey 5	22.8	786	17921	473	446	454	362	334	269
Storey 4	16.8	665	11172	295	278	283	226	208	167
Storey 3	13.2	599	7907	209	197	200	160	147	119
Storey 2	9.6	599	5751	152	143	146	116	107	86
Storey 1	6	675	4050	107	101	103	82	75	61
				11261	10615	10814	8612	7949	6392

4.1.2.3 Modal response spectrum analysis

4.1.2.3.1 General rules

The general rules recommended for this type of analysis, as described in clause 4.3.3.3 of EN 11998-1:2004 were followed in the case of the test building and are given as follows.

- Modal response spectrum analysis is performed independently for the ground excitation in two horizontal directions, excluding the vertical direction since thea_{vg}in vertical direction is less than 0.25 g (2.5m/s²).
- Design spectrum for ductility class medium is used in the test building.
- For the combination of different modes, the "Complete Quadratic Combination (CQC) rule was used(*Clause 4.3.3.3.2 of EN 1998-1:2004).*
- The results of the modal analysis in both directions were combined by the SRSS rule as described in clause 4.3.3.5.1ofEN 1998-1:2004.
- The load combinations were considered according to clause 3.2.4 of EN 1998-1:2004.
- The accidental torsional effects was considered by means of torsional moments about the vertical axis according to clause 4.3.3.3.3 of EN 1998-1: 2004.

4.1.2.3.2 Periods and effective masses

In the modal response spectrum analysis, 12 modes of vibration were taken into account as the sum of the modal masses in each horizontal direction to exceed 90% of the total mass of the structure.

The basic properties of the models are summarized in Table EA-5.

Table EA-5 : Periods and effective modal mass participation of building A (Modal response spectrum analysis)

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	1.64	15.25	48.57
2	1.32	42.46	16.93
3	0.71	0.12	0.10
4	0.36	4.77	14.43
5	0.31	15.11	6.41
6	0.23	1.11	0.18
7	0.16	2.61	1.07
8	0.14	6.19	0.71
9	0.13	0.19	3.42
10	0.11	0.28	0.10
11	0.09	3.33	0.20
12	0.08	0.05	3.18
		91.47%	95.30%

4.1.2.3.3 Torsional effects

As described in section 2.1.5.5, the accidental torsional effect was considered by means of torsional moments ($M_{axi}$and M_{ayi}) applying about the vertical axis at each storey, i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) were added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey level is shown in Table EA-6.

Table EA-6 : Torsional moments at each horizontal direction

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	28.99	18.88	1.45	0.94	925	872	888	707	653	525	870	1264	835	1025	614	761
17	28.99	18.88	1.45	0.94	1140	1074	1094	872	804	647	1072	1557	1028	1264	756	938
16	28.99	18.88	1.45	0.94	1015	957	975	776	716	576	954	1388	917	1125	673	835
15	28.99	18.88	1.45	0.94	956	901	918	731	675	543	899	1306	863	1060	635	787
14	28.99	18.88	1.45	0.94	909	857	873	696	642	516	854	1243	821	1009	603	748
13	28.99	18.88	1.45	0.94	839	791	806	642	592	476	789	1147	758	931	556	690
12	28.99	18.88	1.45	0.94	781	736	750	597	551	443	734	1067	705	866	518	642
11	28.99	18.88	1.45	0.94	722	681	693	552	510	410	679	987	651	800	479	595
10	28.99	18.88	1.45	0.94	664	626	637	507	468	377	624	908	599	735	440	547
9	28.99	18.88	1.45	0.94	605	570	581	463	427	343	569	827	546	671	401	497
8	28.99	18.88	1.45	0.94	546	515	525	418	386	310	513	747	494	606	363	450
7	28.99	18.88	1.45	0.94	488	460	469	373	344	277	459	667	441	541	323	402
6	28.99	18.88	1.45	0.94	435	410	418	333	307	247	409	595	393	483	289	358
5	28.99	18.88	1.45	0.94	473	446	454	362	334	269	445	647	427	525	314	390
4	28.99	18.88	1.45	0.94	295	278	283	226	208	167	277	403	266	328	196	242
3	28.99	18.88	1.45	0.94	209	197	200	160	147	119	196	286	188	232	138	173
2	28.99	18.88	1.45	0.94	152	143	146	116	107	86	143	207	137	168	101	125
1	28.99	18.88	1.45	0.94	107	101	103	82	75	61	101	146	97	119	71	88

4.1.2.3.4 Storey shear and displacement

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.1.5.6.

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table EA-7 and EA-8 respectively.

Table EA-7 : Storey shear forces of building A (Modal response spectrum analysis method)

Storey	Storey Shear (kN)					
	Soft		Medium		Hard	
	X	Y	X	Y	X	Y
Roof	1081	963	1006	898	932	836
17	1789	1633	1633	1501	1479	1374
16	2323	2163	2080	1959	1832	1759
15	2730	2574	2393	2292	2041	2011
14	3054	2893	2622	2530	2158	2159
13	3326	3148	2803	2702	2226	2235
12	3570	3363	2964	2835	2281	2271
11	3804	3557	3130	2954	2362	2295
10	4047	3745	3325	3078	2499	2337
9	4305	3941	3555	3225	2703	2423
8	4572	4157	3810	3408	2958	2573
7	4834	4397	4074	3634	3237	2792
6	5088	4664	4337	3901	3525	3074
5	5502	5165	4780	4425	4017	3649
4	5732	5450	5028	4729	4293	3986
3	5907	5678	5217	4974	4504	4258
2	6025	5842	5345	5152	4646	4456
1	6094	5947	5420	5267	4730	4584

Table EA-8 : displacement (d_s) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_e(m)						q_d	d_s(m)					
	Soft		Medium		Hard			Soft		Medium		Hard	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.0947	0.0997	0.0783	0.0820	0.0596	0.0621	1.60	0.1515	0.1595	0.1253	0.1312	0.0954	0.0994
17	0.0850	0.0906	0.0703	0.0745	0.0534	0.0565	1.60	0.1360	0.1450	0.1125	0.1192	0.0854	0.0904
16	0.0783	0.0845	0.0647	0.0695	0.0491	0.0527	1.60	0.1253	0.1352	0.1035	0.1112	0.0786	0.0843
15	0.0715	0.0784	0.0590	0.0645	0.0447	0.0489	1.60	0.1144	0.1254	0.0944	0.1032	0.0715	0.0782
14	0.0646	0.0723	0.0534	0.0595	0.0404	0.0451	1.60	0.1034	0.1157	0.0854	0.0952	0.0646	0.0722
13	0.0578	0.0661	0.0477	0.0544	0.0361	0.0414	1.60	0.0925	0.1058	0.0763	0.0870	0.0578	0.0662
12	0.0510	0.0599	0.0421	0.0494	0.0319	0.0376	1.60	0.0816	0.0958	0.0674	0.0790	0.0510	0.0602
11	0.0443	0.0538	0.0366	0.0444	0.0277	0.0338	1.60	0.0709	0.0861	0.0586	0.0710	0.0443	0.0541
10	0.0378	0.0478	0.0312	0.0394	0.0237	0.0301	1.60	0.0605	0.0765	0.0499	0.0630	0.0379	0.0482
9	0.0315	0.0418	0.0261	0.0345	0.0198	0.0264	1.60	0.0504	0.0669	0.0418	0.0552	0.0317	0.0422
8	0.0256	0.0359	0.0211	0.0297	0.0161	0.0228	1.60	0.0410	0.0574	0.0338	0.0475	0.0258	0.0365
7	0.0200	0.0303	0.0166	0.0251	0.0127	0.0193	1.60	0.0320	0.0485	0.0266	0.0402	0.0203	0.0309
6	0.0150	0.0249	0.0124	0.0206	0.0095	0.0159	1.60	0.0240	0.0398	0.0198	0.0330	0.0152	0.0254
5	0.0113	0.0200	0.0093	0.0166	0.0072	0.0129	1.60	0.0181	0.0320	0.0149	0.0266	0.0115	0.0206
4	0.0064	0.0121	0.0053	0.0101	0.0041	0.0079	1.60	0.0102	0.0194	0.0085	0.0162	0.0066	0.0126
3	0.0043	0.0081	0.0036	0.0068	0.0028	0.0054	1.60	0.0069	0.0130	0.0058	0.0109	0.0045	0.0086
2	0.0025	0.0047	0.0021	0.0040	0.0017	0.0032	1.60	0.0040	0.0075	0.0034	0.0064	0.0027	0.0051
1	0.0011	0.0021	0.0010	0.0018	0.0008	0.0015	1.60	0.0018	0.0034	0.0016	0.0029	0.0013	0.0024

4.1.2.3.5 Inter-storey drift

The inter-storey drift (d_r) was evaluated as described in section 2.1.5.6.2, considering the difference of the lateral displacements (d_s) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_r) was then checked for damage limitation requirement given by the following equation ,

$$d_r \nu \leq (\propto).\mathrm{h}$$

Since the structure is of importance level III, the ν value was selected to 0.4.

All parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in tables EA-9, EA-10 and EA-11 for soft, medium and hard soil conditions respectively.

Table EA-9 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Soft soil conditions

Storey	d_r (m)		h	ν	$d_r*\nu/h$		α		
	X-dir	Y-dir	(m)		X-dir	Y-dir			
Roof	0.0155	0.0146	5.2	0.4	0.0012	0.0011			
Storey 17	0.0107	0.0098	3.6	0.4	0.0012	0.0011			
Storey 16	0.0109	0.0098	3.6	0.4	0.0012	0.0011			
Storey 15	0.0110	0.0098	3.6	0.4	0.0012	0.0011			
Storey 14	0.0109	0.0099	3.6	0.4	0.0012	0.0011			
Storey 13	0.0109	0.0099	3.6	0.4	0.0012	0.0011			
Storey 12	0.0107	0.0098	3.6	0.4	0.0012	0.0011			
Storey 11	0.0104	0.0096	3.6	0.4	0.0012	0.0011	0.005	0.0075	0.01
Storey 10	0.0101	0.0096	3.6	0.4	0.0011	0.0011			
Storey 9	0.0094	0.0094	3.6	0.4	0.001	0.001			
Storey 8	0.0090	0.0090	3.6	0.4	0.001	0.001			
Storey 7	0.0080	0.0086	3.6	0.4	0.0009	0.001			
Storey 6	0.0059	0.0078	3.6	0.4	0.0007	0.0009			
Storey 5	0.0078	0.0126	6	0.4	0.0005	0.0008			
Storey 4	0.0034	0.0064	3.6	0.4	0.0004	0.0007			
Storey 3	0.0029	0.0054	3.3	0.4	0.0003	0.0007			
Storey 2	0.0022	0.0042	3.6	0.4	0.0002	0.0005			
Storey 1	0.0018	0.0034	6	0.4	0.0001	0.0002			

Table EA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Medium soil conditions

Storey	d_r(m)		h	v	$d_r * v / h$		α		
	X-dir	Y-dir	(m)		X-dir	Y-dir			
Roof	0.0128	0.0120	5.2	0.4	0.001	0.0009			
Storey 17	0.0090	0.0080	3.6	0.4	0.001	0.0009			
Storey 16	0.0091	0.0080	3.6	0.4	0.001	0.0009			
Storey 15	0.0090	0.0080	3.6	0.4	0.001	0.0009			
Storey 14	0.0091	0.0082	3.6	0.4	0.001	0.0009			
Storey 13	0.0090	0.0080	3.6	0.4	0.001	0.0009			
Storey 12	0.0088	0.0080	3.6	0.4	0.001	0.0009			
Storey 11	0.0086	0.0080	3.6	0.4	0.001	0.0009	0.005	0.0075	0.01
Storey 10	0.0082	0.0078	3.6	0.4	0.0009	0.0009			
Storey 9	0.0080	0.0077	3.6	0.4	0.0009	0.0009			
Storey 8	0.0072	0.0074	3.6	0.4	0.0008	0.0008			
Storey 7	0.0067	0.0072	3.6	0.4	0.0007	0.0008			
Storey 6	0.0050	0.0064	3.6	0.4	0.0006	0.0007			
Storey 5	0.0064	0.0104	6	0.4	0.0004	0.0007			
Storey 4	0.0027	0.0053	3.6	0.4	0.0003	0.0006			
Storey 3	0.0024	0.0045	3.3	0.4	0.0003	0.0005			
Storey 2	0.0018	0.0035	3.6	0.4	0.0002	0.0004			
Storey 1	0.0016	0.0029	6	0.4	0.0001	0.0002			

Table EA-11 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Hard soil conditions

Storey	d_r(m)		h	v	$d_r * v / h$		α		
	X-dir	Y-dir	(m)		X-dir	Y-dir			
Roof	0.0099	0.0090	5.2	0.4	0.0008	0.0007			
Storey 17	0.0069	0.0061	3.6	0.4	0.0008	0.0007			
Storey 16	0.0070	0.0061	3.6	0.4	0.0008	0.0007			
Storey 15	0.0069	0.0061	3.6	0.4	0.0008	0.0007			
Storey 14	0.0069	0.0059	3.6	0.4	0.0008	0.0007			
Storey 13	0.0067	0.0061	3.6	0.4	0.0007	0.0007			
Storey 12	0.0067	0.0061	3.6	0.4	0.0007	0.0007			
Storey 11	0.0064	0.0059	3.6	0.4	0.0007	0.0007	0.005	0.0075	0.01
Storey 10	0.0062	0.0059	3.6	0.4	0.0007	0.0007			
Storey 9	0.0059	0.0058	3.6	0.4	0.0007	0.0006			
Storey 8	0.0054	0.0056	3.6	0.4	0.0006	0.0006			
Storey 7	0.0051	0.0054	3.6	0.4	0.0006	0.0006			
Storey 6	0.0037	0.0048	3.6	0.4	0.0004	0.0005			
Storey 5	0.0050	0.0080	6	0.4	0.0003	0.0005			
Storey 4	0.0021	0.0040	3.6	0.4	0.0002	0.0004			
Storey 3	0.0018	0.0035	3.3	0.4	0.0002	0.0004			
Storey 2	0.0014	0.0027	3.6	0.4	0.0002	0.0003			
Storey 1	0.0013	0.0024	6	0.4	0.0001	0.0002			

4.1.2.3.6 P-Δ effects

As described in section 2.1.5.7, the P-Δ effects was checked according to the equation given as,

$$\theta = \frac{P_{tot}.d_r}{V_{tot}.h} \leq 0.10$$

Where,

P_{tot}: Is the total gravity load, including appropriate amount of imposed load at and above the storey considered in the seismic design situation – From table EA-1.

d_r: Is the inter-storey drift – From table EA-9, EA-10, EA-11 as appropriately for particular soil type.

V_{tot}: Is the total seismic storey shear from response spectrum analysis.

h : Floor to floor height.

The calculation of the inter-storey drift sensitivity coefficient from modal response spectrum analysis are shown in Table EA-12, EA-13 and EA-14 for soft, medium and hard soil conditions respectively.

Table EA-12 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Soft soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	4,827	0.0012	0.0011	1081	963	5.2	0.001	0.001
Storey 17	11,242	0.0012	0.0011	1789	1633	3.6	0.002	0.002
Storey 16	17,285	0.0012	0.0011	2323	2163	3.6	0.002	0.002
Storey 15	23,328	0.0012	0.0011	2730	2574	3.6	0.003	0.003
Storey 14	29,371	0.0012	0.0011	3054	2893	3.6	0.003	0.003
Storey 13	35,414	0.0012	0.0011	3326	3148	3.6	0.004	0.003
Storey 12	41,457	0.0012	0.0011	3570	3363	3.6	0.004	0.004
Storey 11	47,500	0.0012	0.0011	3804	3557	3.6	0.004	0.004
Storey 10	53,543	0.0011	0.0011	4047	3745	3.6	0.004	0.004
Storey 9	59,586	0.0010	0.0010	4305	3941	3.6	0.004	0.004
Storey 8	65,629	0.0010	0.0010	4572	4157	3.6	0.004	0.004
Storey 7	71,672	0.0009	0.0010	4834	4397	3.6	0.004	0.005
Storey 6	77,793	0.0007	0.0009	5088	4664	3.6	0.003	0.004
Storey 5	85,504	0.0005	0.0008	5502	5165	6	0.001	0.002
Storey 4	92,028	0.0004	0.0007	5732	5450	3.6	0.002	0.003
Storey 3	97,904	0.0003	0.0007	5907	5678	3.3	0.002	0.004
Storey 2	103,780	0.0002	0.0005	6025	5842	3.6	0.001	0.002
Storey 1	110,402	0.0001	0.0002	6094	5947	3.6	0.001	0.001

Table EA-13 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Medium soil conditions

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	4,827	0.0128	0.0120	1006	898	5.2	0.012	0.012
Storey 17	11,046	0.0090	0.0080	1633	1501	3.6	0.017	0.016
Storey 16	16,893	0.0091	0.0080	2080	1959	3.6	0.021	0.019
Storey 15	22,740	0.0090	0.0080	2393	2292	3.6	0.024	0.022
Storey 14	28,586	0.0091	0.0082	2622	2530	3.6	0.028	0.026
Storey 13	34,433	0.0090	0.0080	2803	2702	3.6	0.031	0.028
Storey 12	40,280	0.0088	0.0080	2964	2835	3.6	0.033	0.032
Storey 11	46,127	0.0086	0.0080	3130	2954	3.6	0.035	0.035
Storey 10	51,973	0.0082	0.0078	3325	3078	3.6	0.035	0.037
Storey 9	57,820	0.0080	0.0077	3555	3225	3.6	0.036	0.038
Storey 8	63,667	0.0072	0.0074	3810	3408	3.6	0.033	0.038
Storey 7	69,514	0.0067	0.0072	4074	3634	3.6	0.032	0.038
Storey 6	75,439	0.0050	0.0064	4337	3901	3.6	0.024	0.034
Storey 5	82,953	0.0064	0.0104	4780	4425	6	0.019	0.032
Storey 4	89,114	0.0027	0.0053	5028	4729	3.6	0.013	0.028
Storey 3	94,627	0.0024	0.0045	5217	4974	3.3	0.013	0.026
Storey 2	100,140	0.0018	0.0035	5345	5152	3.6	0.009	0.019
Storey 1	106,399	0.0016	0.0029	5420	5267	6	0.005	0.01

Table EA-14 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Hard soil conditions

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	4,827	0.0099	0.0090	932	836	5.2	0.01	0.01
Storey 17	11,242	0.0069	0.0061	1479	1374	3.6	0.015	0.014
Storey 16	17,285	0.0070	0.0061	1832	1759	3.6	0.018	0.017
Storey 15	23,328	0.0069	0.0061	2041	2011	3.6	0.022	0.02
Storey 14	29,371	0.0069	0.0059	2158	2159	3.6	0.026	0.022
Storey 13	35,414	0.0067	0.0061	2226	2235	3.6	0.03	0.027
Storey 12	41,457	0.0067	0.0061	2281	2271	3.6	0.034	0.031
Storey 11	47,500	0.0064	0.0059	2362	2295	3.6	0.036	0.034
Storey 10	53,543	0.0062	0.0059	2499	2337	3.6	0.037	0.038
Storey 9	59,586	0.0059	0.0058	2703	2423	3.6	0.036	0.039
Storey 8	65,629	0.0054	0.0056	2958	2573	3.6	0.034	0.04
Storey 7	71,672	0.0051	0.0054	3237	2792	3.6	0.031	0.039
Storey 6	77,793	0.0037	0.0048	3525	3074	3.6	0.023	0.034
Storey 5	85,504	0.0050	0.0080	4017	3649	6	0.018	0.031
Storey 4	92,028	0.0021	0.0040	4293	3986	3.6	0.012	0.026
Storey 3	97,904	0.0018	0.0035	4504	4258	3.3	0.012	0.025
Storey 2	103,780	0.0014	0.0027	4646	4456	3.6	0.009	0.018
Storey 1	110,402	0.0013	0.0024	4730	4584	3.6	0.008	0.016

4.2 BUILDING "B"

4.2.1 Design seismic action

Classification of building

Since this is an apartment building having more than 10 storeys, the structure has been categorized as importance level III (*Table EN-1*)

Design peak ground acceleration

Since $a_{g,475} = 0.1g$ (*Table EN-2)* and

$\gamma_1 = 1.5$ (*Table EN-2)*

The design peak ground acceleration value was then calculated as,

$a_g = (0.1g \times 1.5) = 0.15g$

Behavior factor (q)

This building has been designed for Ductility Class Medium (DCM) conditions. The behavior factor, q for this building, according to Clause 5.2.2.2 of EN 1998-1:2004,

$$q = q_0 k_w$$

The structural type of the building has been considered as torsionally flexible system. The q_0 for a torsionally flexible system, which is regular in elevation is given as,

$q_0 = 2.0$ (*Table EN-4*)

Since the selected building is irregular in elevation, 80% of the q_0 has to be used in calculations, as described in appendix A-2.1.2.

For a torsionally flexible system,

$k_w = (1 + \alpha_0)/3 \leq 1$, but not less than 0.5 (*Table EN-5*)

And,

$$\propto_0 = \sum h_{wi} / \sum l_{wi}$$

$\propto_0 = 17.28$

Therefore,

$$k_w = (1+17.28)/3$$

Therefore, k_w can be taken as 1.0

Therefore,

$$q = (0.8\times2\times 1) = 1.6$$

Elastic response spectrum and design response spectrum for three different types of soil conditions and are shown in figure EB-1.

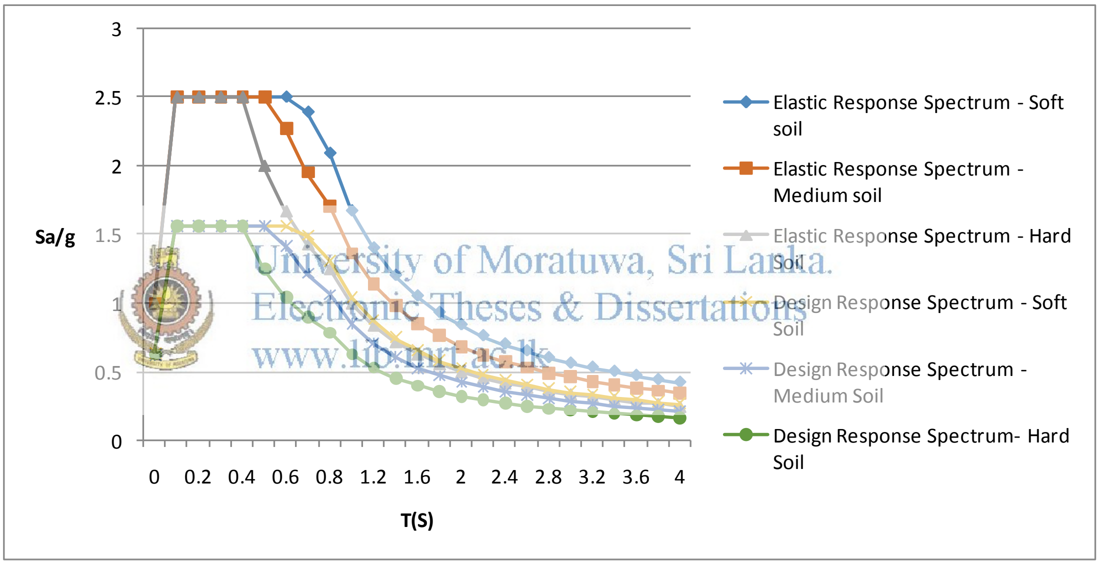

Figure EB-1:Elastic response spectrum and design response spectrum -Building B

4.2.2 Method of analysis

A modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis was also performed in order to obtain the horizontal force acting on each storey, which was used to determine accidental torsional effects as described in section 2.1.5.5.

All the computer analysis were performed with the ETABs software (CSI 2002. ETABS Integrated Building Design Software, Computers and Structures Inc. Berkley).

4.2.2.1 Structural Model

The EC 8 recommends using a spatial model as the preference method for all type of buildings(*Clause 4.3.1of EN 1998-1:2004*). On account of that, for the test building a three dimensional (spatial) model was developed. The computer model of this building was created in a similar way as described in section 4.1.2.1, in case of building A.

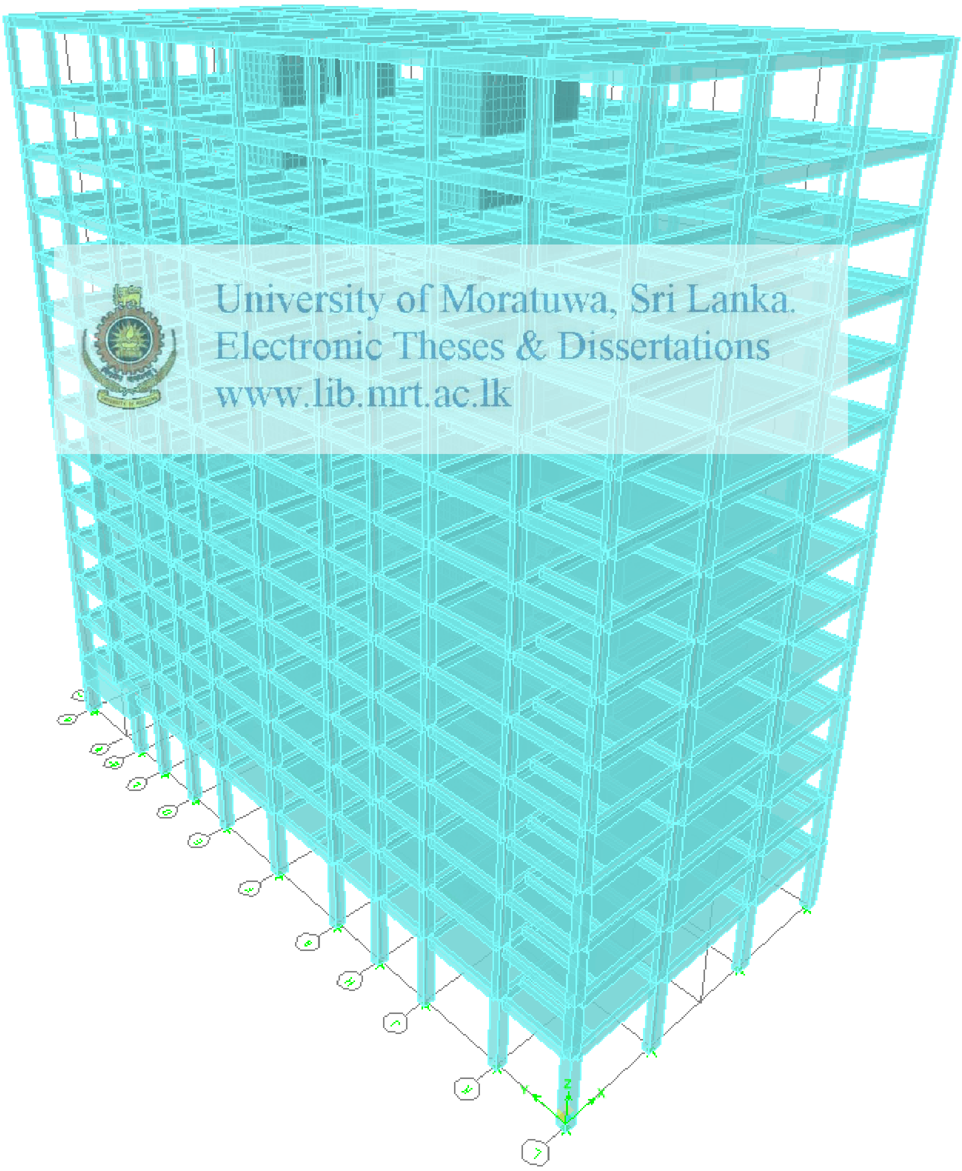

Figure EB-2 : Three dimensional (spatial) model of building B

4.2.2.2 Lateral force method of analysis

As described in section 4.1.2.2, the method of analysis has been carried out in three main steps as follows.

a) Estimating the self-weight and seismic masses of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces and moments

4.2.2.2.1 Estimation of seismic mass of the building

As described in section 2.1.5.1, the seismic mass of the building was taken as the following combination of dead load and the variable loads as,

$$\sum G_{k,j} + \sum \upsilon_{E,i} Q_{k,I}$$

Table EB-1 : Total seismic mass of building B

Storey	ψ_2 (Table EN-7)	φ (Table EN-9)	$G_{k,j}$ (t) (Table B-3)	$Q_{k,I}$ (t) (Table B-4)	Seismic mass (t)	Total Seismic mass (t)
Roof	0	0	761	183	761	761
Storey 13	0.3	0.8	989	183	1033	1033
Storey 12	0.3	0.8	974	183	1018	1018
Storey 11	0.3	0.8	987	183	1031	1031
Storey 8-10	0.3	0.8	997	183	1041	3123
Storey 7	0.3	0.8	1001	183	1045	1045
Storey 5-6	0.3	0.8	1004	183	1048	2096
Storey 4	0.3	0.8	1015	183	1059	1059
Storey 2-3	0.3	0.8	1024	183	1068	2136
Storey 1	0.3	0.8	1203	183	1247	1247
Total seismic mass of the building						14,549

4.2.2.2.2 Calculating seismic base shear

As described in section 2.1.5.4.1, the seismic base shear force for each horizontal direction was determined by the following equation,

$$F_b = S_d(T_1).m.\lambda$$

T_1: The fundamental period of the building – Refer table B5

$S_d(T_1)$: The value of the ordinate of the design response spectrum, corresponding to the fundamental period T_1 of the building for different soil conditions – Refer figure EB-1

m: The seismic mass of the building - Refer table EB-1

λ : The correction factor, λ can be determined according to clause 4.3.3.2.2 of EN 1998-1: 2004. The values of λ for three different soil conditions are shown in table EB-2.

The base shear force for each horizontal directions for three soil conditions are shown in Table EB-3.

Table EB-2 : Correction factor, λ for building B

Soil Type	T_c	$2T_c$	T_x	T_y	λ_x	λ_y
Soft	0.67	1.34	1.44	1.59	1.00	1.00
Medium	0.55	1.10	1.44	1.59	1.00	1.00
Hard	0.40	0.80	1.44	1.59	1.00	1.00

Table EB-3 : Seismic base shear of building B

Soil Type	Fundamental Period (T_1)		$S_d(T_1)$		m (t)	λ		F_b (kN)	
	X	Y	X	Y		X	Y	X	Y
Soft	1.44	1.59	1.0771	0.9727	14,549	1.00	1.00	15671	14152
Medium	1.44	1.59	0.8538	0.7874	14,549	1.00	1.00	12422	11456
Hard	1.44	1.59	0.646	0.5842	14,549	1.00	1.00	9399	8500

4.2.2.2.3 Distribution of lateral forces

The seismic base shear (F_b) was distributed at each storey level by using the following expression as shown in section 2.1.5.4.1(C),

$$F_i = F_b . \frac{z_i . m_i}{\sum z_j . m_j}$$

Distribution of seismic base shear at each storey level is shown in Table EB-4.

Table EB-4 : Distribution of seismic base shear at each storey level - Building B

Storey	Height (z_i) (m)	Mass (m_i) (t)	$Z_i.m_i$ (tm)	Fi(kN)					
				Soft		Medium		Hard	
				F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}
Roof	46.3	761	35235	1567	1415	1242	1145	940	850
Storey 13	42.3	1033	43696	1943	1755	1540	1421	1165	1054
Storey 12	39.15	1018	39855	1772	1601	1405	1296	1063	961
Storey 11	36	1031	37116	1651	1491	1308	1207	990	895
Storey 10	32.85	1041	34197	1521	1373	1205	1112	912	825
Storey 9	29.7	1041	30918	1375	1242	1090	1005	825	746
Storey 8	26.55	1041	27639	1229	1110	974	899	737	667
Storey 7	23.45	1045	24506	1090	984	864	797	654	591
Storey 6	20.25	1048	21222	944	852	748	690	566	512
Storey 5	17.1	1048	17921	797	720	632	583	478	432
Storey 4	13.95	1059	14774	657	593	521	480	394	356
Storey 3	10.8	1068	11535	513	463	407	375	308	278
Storey 2	7.65	1068	8171	363	328	288	266	218	197
Storey 1	4.5	1247	5612	250	225	198	182	150	135
				15671	14152	12422	11456	9399	8500

4.2.2.3 Modal response spectrum analysis

4.2.2.3.1 General rules

The general rules recommended for this type of analysis, as described in clause 4.3.3.3 of EN 11998-1:2004 were followed in the case of the test building in a similar way as in building A, which is described in section 4.1.2.3.1.

4.2.2.3.2 Periods and effective masses

In the modal response spectrum analysis, 12 modes of vibration were taken in to account as the sum of the modal masses in each horizontal directions to exceed 90% of the total mass of the structure.

The basic properties of the models are summarized in Table EB-5.

Table EB-5 : Periods and effective modal mass participation of building B (Modal response spectrum analysis)

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	1.73	0.58	21.24
2	1.59	0.86	46.59
3	1.44	70.86	0.12
4	0.54	0.08	1.17
5	0.42	12.07	2.45
6	0.41	1.75	14.51
7	0.28	0.01	0.36
8	0.20	6.06	0.02
9	0.18	0.01	6.51
		92.28%	92.97%

4.2.2.3.3 Torsional effects

As described in section 2.1.5.5, the accidental torsional effect was considered by means of torsional moments (M_{axi} and M_{ayi}) applying about the vertical axis at each storey, i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) were added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces (F_{ix} and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey level is shown in Table EB-6.

Table EB-6 : Torsional moments at each horizontal direction

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	20.6	44.3	1.03	2.215	1567	1415	1242	1145	940	850	3471	1457	2751	1179	2082	876
Storey 13	20.6	44.3	1.03	2.215	1943	1755	1540	1421	1165	1054	4304	1808	3411	1464	2580	1086
Storey 12	20.6	44.3	1.03	2.215	1772	1601	1405	1296	1063	961	3925	1649	3112	1335	2355	990
Storey 11	20.6	44.3	1.03	2.215	1651	1491	1308	1207	990	895	3657	1536	2897	1243	2193	922
Storey 10	20.6	44.3	1.03	2.215	1521	1373	1205	1112	912	825	3369	1414	2669	1145	2020	850
Storey 9	20.6	44.3	1.03	2.215	1375	1242	1090	1005	825	746	3046	1279	2414	1035	1827	768
Storey 8	20.6	44.3	1.03	2.215	1229	1110	974	899	737	667	2722	1143	2157	926	1632	687
Storey 7	20.6	44.3	1.03	2.215	1090	984	864	797	654	591	2414	1014	1914	821	1449	609
Storey 6	20.6	44.3	1.03	2.215	944	852	748	690	566	512	2091	878	1657	711	1254	527
Storey 5	20.6	44.3	1.03	2.215	797	720	632	583	478	432	1765	742	1400	600	1059	445
Storey 4	20.6	44.3	1.03	2.215	657	593	521	480	394	356	1455	611	1154	494	873	367
Storey 3	20.6	44.3	1.03	2.215	513	463	407	375	308	278	1136	477	902	386	682	286
Storey 2	20.6	44.3	1.03	2.215	363	328	288	266	218	197	804	338	638	274	483	203
Storey 1	20.6	44.3	1.03	2.215	250	225	198	182	150	135	554	232	439	187	332	139

4.2.2.3.4. Storey shear and displacement

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.1.5.6.

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table EB-7 and EB-8 only.

Table EB-7 : Storey shear forces of building B (Modal response spectrum analysis Method)

Storey	Storey Shear (kN)					
	Soft		Medium		Hard	
	X	Y	X	Y	X	Y
Roof	1326	1284	1231	1212	1120	1128
Storey 13	2384	2221	2166	2053	1916	1867
Storey 12	3158	2828	2806	2552	2405	2254
Storey 11	3769	3236	3269	2838	2701	2409
Storey 10	4293	3552	3643	3024	2901	2455
Storey 9	4769	3845	3979	3201	3075	2501
Storey 8	5210	4148	4300	3412	3254	2608
Storey 7	5622	4470	4613	3670	3450	2796
Storey 6	6011	4816	4930	3983	3681	3074
Storey 5	6386	5186	5264	4348	3967	3437
Storey 4	6749	5572	5613	4749	4305	3860
Storey 3	7071	5931	5937	5132	4641	4274
Storey 2	7298	6200	6174	5422	4895	4589
Storey 1	7441	6380	6326	5618	5061	4803

Table EB-8 : Design displacement (d_s) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_e(m)						q_d	d_s(m)					
	Soft		Medium		Hard			Soft		Medium		Hard	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.0838	0.0915	0.0688	0.0746	0.0514	0.0558	1.60	0.1341	0.1464	0.1101	0.1194	0.0822	0.0893
Storey 13	0.0777	0.0825	0.0637	0.0672	0.0475	0.0502	1.60	0.1243	0.1320	0.1019	0.1075	0.0760	0.0803
Storey 12	0.0727	0.0754	0.0596	0.0614	0.0443	0.0458	1.60	0.1163	0.1206	0.0954	0.0982	0.0709	0.0733
Storey 11	0.0672	0.0681	0.0550	0.0554	0.0409	0.0413	1.60	0.1075	0.1090	0.0880	0.0886	0.0654	0.0661
Storey 10	0.0614	0.0608	0.0503	0.0495	0.0373	0.0369	1.60	0.0982	0.0973	0.0805	0.0792	0.0597	0.0590
Storey 9	0.0552	0.0534	0.0452	0.0435	0.0336	0.0325	1.60	0.0883	0.0854	0.0723	0.0696	0.0538	0.0520
Storey 8	0.0486	0.0460	0.0398	0.0375	0.0297	0.0281	1.60	0.0778	0.0736	0.0637	0.0600	0.0475	0.0450
Storey 7	0.0417	0.0386	0.0342	0.0316	0.0256	0.0238	1.60	0.0667	0.0618	0.0547	0.0506	0.0410	0.0381
Storey 6	0.0346	0.0314	0.0285	0.0258	0.0214	0.0195	1.60	0.0554	0.0502	0.0456	0.0413	0.0342	0.0312
Storey 5	0.0275	0.0245	0.0227	0.0201	0.0171	0.0154	1.60	0.0440	0.0392	0.0363	0.0322	0.0274	0.0246
Storey 4	0.0205	0.0179	0.0169	0.0148	0.0129	0.0114	1.60	0.0328	0.0286	0.0270	0.0237	0.0206	0.0182
Storey 3	0.0139	0.0121	0.0115	0.0100	0.0088	0.0078	1.60	0.0222	0.0194	0.0184	0.0160	0.0141	0.0125
Storey 2	0.0081	0.0070	0.0067	0.0059	0.0052	0.0046	1.60	0.0130	0.0112	0.0107	0.0094	0.0083	0.0074
Storey 1	0.0037	0.0031	0.0031	0.0026	0.0024	0.0021	1.60	0.0059	0.0050	0.0050	0.0042	0.0038	0.0034

4.2.2.3.5Inter-storey drift

The inter-storey drift (d_r) was evaluated as described in section 2.1.5.6.2, considering the difference of the lateral displacements (d_s) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_r) was then checked for damage limitation requirement given by the following equation ,

$$d_r \nu \leq (\propto).\mathrm{h}$$

Since the structure is of importance level III, the ν value was selected to 0.4.

All parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in tables EB-9, EB-10 and EB-11 for soft, medium and hard soil conditions respectively.

Table EB-9 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Soft soil conditions

Storey	d_r (m)		h	v	d_r * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0098	0.0144	4	0.4	0.001	0.0014	
Storey 13	0.0080	0.0114	3.15	0.4	0.001	0.0014	
Storey 12	0.0088	0.0117	3.15	0.4	0.0011	0.0015	
Storey 11	0.0093	0.0117	3.15	0.4	0.0012	0.0015	
Storey 10	0.0099	0.0118	3.15	0.4	0.0013	0.0015	
Storey 9	0.0106	0.0118	3.15	0.4	0.0013	0.0015	
Storey 8	0.0110	0.0118	3.15	0.4	0.0014	0.0015	0.005 0.0075 0.01
Storey 7	0.0114	0.0115	3.15	0.4	0.0014	0.0015	
Storey 6	0.0114	0.0110	3.15	0.4	0.0014	0.0014	
Storey 5	0.0112	0.0106	3.15	0.4	0.0014	0.0013	
Storey 4	0.0106	0.0093	3.15	0.4	0.0013	0.0012	
Storey 3	0.0093	0.0082	3.15	0.4	0.0012	0.001	
Storey 2	0.0070	0.0062	3.15	0.4	0.0009	0.0008	
Storey 1	0.0059	0.0050	4.5	0.4	0.0005	0.0004	

Table EB-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Medium soil conditions

Storey	d_r (m)		h	v	dr * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0082	0.0118	4	0.4	0.0008	0.0012	
Storey 13	0.0066	0.0093	3.15	0.4	0.0008	0.0012	
Storey 12	0.0074	0.0096	3.15	0.4	0.0009	0.0012	
Storey 11	0.0075	0.0094	3.15	0.4	0.001	0.0012	
Storey 10	0.0082	0.0096	3.15	0.4	0.001	0.0012	
Storey 9	0.0086	0.0096	3.15	0.4	0.0011	0.0012	
Storey 8	0.0090	0.0094	3.15	0.4	0.0011	0.0012	0.005 0.0075 0.01
Storey 7	0.0091	0.0093	3.15	0.4	0.0012	0.0012	
Storey 6	0.0093	0.0091	3.15	0.4	0.0012	0.0012	
Storey 5	0.0093	0.0085	3.15	0.4	0.0012	0.0011	
Storey 4	0.0086	0.0077	3.15	0.4	0.0011	0.001	
Storey 3	0.0077	0.0066	3.15	0.4	0.001	0.0008	
Storey 2	0.0058	0.0053	3.15	0.4	0.0007	0.0007	
Storey 1	0.0050	0.0042	4.5	0.4	0.0004	0.0004	

Table EB-11 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Hard soil conditions

Storey	d_r (m)		h	v	d_r * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0062	0.0090	4	0.4	0.0006	0.0009	
Storey 13	0.0051	0.0070	3.15	0.4	0.0007	0.0009	
Storey 12	0.0054	0.0072	3.15	0.4	0.0007	0.0009	
Storey 11	0.0058	0.0070	3.15	0.4	0.0007	0.0009	
Storey 10	0.0059	0.0070	3.15	0.4	0.0008	0.0009	
Storey 9	0.0062	0.0070	3.15	0.4	0.0008	0.0009	
Storey 8	0.0066	0.0069	3.15	0.4	0.0008	0.0009	0.005 0.0075 0.01
Storey 7	0.0067	0.0069	3.15	0.4	0.0009	0.0009	
Storey 6	0.0069	0.0066	3.15	0.4	0.0009	0.0008	
Storey 5	0.0067	0.0064	3.15	0.4	0.0009	0.0008	
Storey 4	0.0066	0.0058	3.15	0.4	0.0008	0.0007	
Storey 3	0.0058	0.0051	3.15	0.4	0.0007	0.0007	
Storey 2	0.0045	0.0040	3.15	0.4	0.0006	0.0005	
Storey 1	0.0038	0.0034	4.5	0.4	0.0003	0.0003	

4.2.2.3.6 P-Δ effects

As described in section 2.1.5.7, the P-Δ effects was checked according to the equation given as,

$$\theta = \frac{P_{tot}.\,d_r}{V_{tot}.\,h} \leq 0.10$$

Where,

P_{tot}: Is the total gravity load, including appropriate amount of imposed load at and above the storey considered in the seismic design situation – From table EB-1.

d_r: Is the inter-storey drift – From table EB-9, EB-10, EB-11 as appropriately for particular soil type.

V_{tot}: Is the total seismic storey shear from response spectrum analysis.

h : Floor to floor height.

The calculation of the inter-storey drift sensitivity coefficient from modal response spectrum analysis are shown in Table EB-12, EB-13 and EB-14 for soft, medium and hard soil conditions respectively.

Table EB-12 : Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Soft soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h (m)	θ	
		X	Y	X	Y		X	Y
Roof	7,465	0.0098	0.0144	1326	1284	4	0.014	0.021
Storey 13	17,599	0.0080	0.0114	2384	2221	3.15	0.019	0.029
Storey 12	27,586	0.0088	0.0117	3158	2828	3.15	0.024	0.036
Storey 11	37,700	0.0093	0.0117	3769	3236	3.15	0.029	0.043
Storey 10	47,912	0.0099	0.0118	4293	3552	3.15	0.035	0.051
Storey 9	58,124	0.0106	0.0118	4769	3845	3.15	0.041	0.057
Storey 8	68,336	0.0110	0.0118	5210	4148	3.15	0.046	0.062
Storey 7	78,588	0.0114	0.0115	5622	4470	3.15	0.05	0.064
Storey 6	88,869	0.0114	0.0110	6011	4816	3.15	0.053	0.065
Storey 5	99,150	0.0112	0.0106	6386	5186	3.15	0.055	0.064
Storey 4	109,538	0.0106	0.0093	6749	5572	3.15	0.054	0.058
Storey 3	120,016	0.0093	0.0082	7071	5931	3.15	0.05	0.052
Storey 2	130,493	0.0070	0.0062	7298	6200	3.15	0.04	0.042
Storey 1	142,726	0.0059	0.0050	7441	6380	4.5	0.025	0.025

Table EB-13 : Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Medium soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h (m)	θ	
		X	Y	X	Y		X	Y
Roof	7,465	0.0082	0.0118	1231	1212	4	0.012	0.018
Storey 13	17,599	0.0066	0.0093	2166	2053	3.15	0.017	0.025
Storey 12	27,586	0.0074	0.0096	2806	2552	3.15	0.023	0.033
Storey 11	37,700	0.0075	0.0094	3269	2838	3.15	0.028	0.04
Storey 10	47,912	0.0082	0.0096	3643	3024	3.15	0.034	0.048
Storey 9	58,124	0.0086	0.0096	3979	3201	3.15	0.04	0.055
Storey 8	68,336	0.0090	0.0094	4300	3412	3.15	0.045	0.06
Storey 7	78,588	0.0091	0.0093	4613	3670	3.15	0.049	0.063
Storey 6	88,869	0.0093	0.0091	4930	3983	3.15	0.053	0.065
Storey 5	99,150	0.0093	0.0085	5264	4348	3.15	0.055	0.061
Storey 4	109,538	0.0086	0.0077	5613	4749	3.15	0.054	0.056
Storey 3	120,016	0.0077	0.0066	5937	5132	3.15	0.049	0.049
Storey 2	130,493	0.0058	0.0053	6174	5422	3.15	0.039	0.04
Storey 1	142,726	0.0050	0.0042	6326	5618	4.5	0.025	0.023

Table EB-14 : Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Hard soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h (m)	θ	
		X	Y	X	Y		X	Y
Roof	7,465	0.0062	0.0090	1120	1128	4	0.01	0.015
Storey 13	17,599	0.0051	0.0070	1916	1867	3.15	0.015	0.021
Storey 12	27,586	0.0054	0.0072	2405	2254	3.15	0.02	0.028
Storey 11	37,700	0.0058	0.0070	2701	2409	3.15	0.026	0.035
Storey 10	47,912	0.0059	0.0070	2901	2455	3.15	0.031	0.044
Storey 9	58,124	0.0062	0.0070	3075	2501	3.15	0.037	0.052
Storey 8	68,336	0.0066	0.0069	3254	2608	3.15	0.044	0.057
Storey 7	78,588	0.0067	0.0069	3450	2796	3.15	0.049	0.061
Storey 6	88,869	0.0069	0.0066	3681	3074	3.15	0.053	0.06
Storey 5	99,150	0.0067	0.0064	3967	3437	3.15	0.053	0.059
Storey 4	109,538	0.0066	0.0058	4305	3860	3.15	0.053	0.052
Storey 3	120,016	0.0058	0.0051	4641	4274	3.15	0.047	0.046
Storey 2	130,493	0.0045	0.0040	4895	4589	3.15	0.038	0.036
Storey 1	142,726	0.0038	0.0034	5061	4803	4.5	0.024	0.022

4.3 BUILDING "C"

4.3.1 Design seismic action

Classification of building

Since this is an apartment building having 10 storeys, the structure has been categorized as importance level III (*Table EN1*).

Design peak ground acceleration

Since $a_{g,475} = 0.1g$ (*Table EN-2)* and

$\gamma_1 = 1.5$ (*Table EN-2)*

The design peak ground acceleration value was then calculated as

a_g = (0.1g × 1.5) = 0.15g

Behavior factor (q)

This building has been designed for Ductility Class Medium (DCM) conditions. The behavior factor, q for this building, according to Clause 5.2.2.2 of EN 1998-1:2004,

$$q = q_0 k_w$$

The structural type of the building has been considered as torsionally flexible system. Theq_0 for a torsionally flexible system, which is regular in elevation is given as,

$q_0 = 2.0$ (*Table EN-4*)

For a torsionally flexible system,

$k_w = (1 + \alpha_0)/3 \leq 1$, but not less than 0.5 (*Table EN-5*)

And,

$$\propto_0 = \sum h_{wi} / \sum l_{wi}$$

$\propto_0 = 9.96$

Therefore,

$k_w = (1+9.96)/3$

Therefore, k_w can be taken as 1.0

Therefore,

q = (2× 1) = 2.0

Elastic response spectrum and design response spectrum for three different types of soil conditions and are shown in figure EC-1.

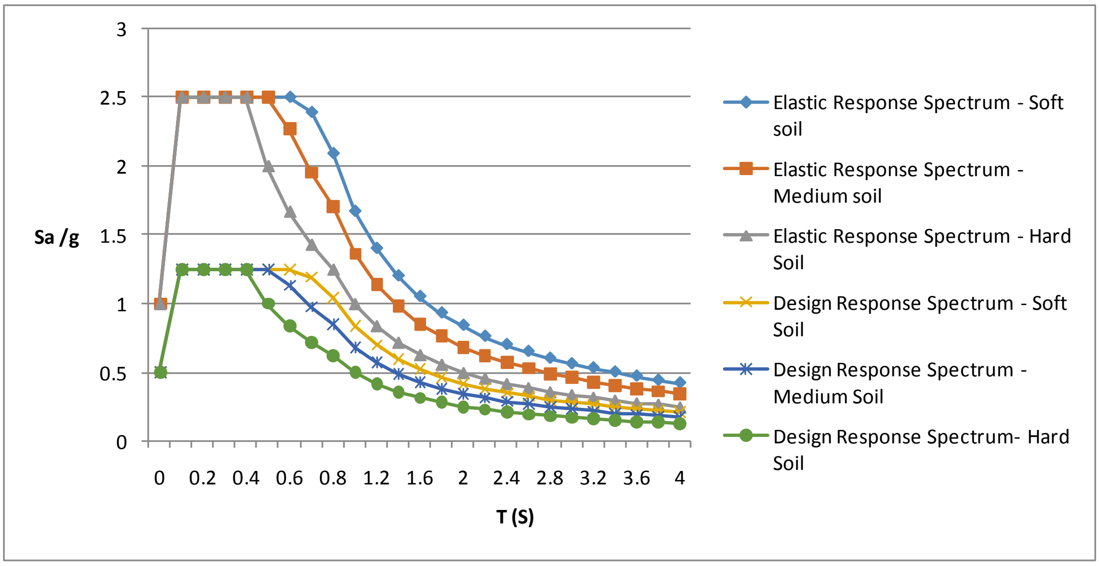

Figure EC-1 : Elastic response spectrum and design response spectrum - Building C

4.3.2 Methods of analysis

A modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis was also performed in order to obtain the horizontal force acting on each storey, which was used to determine accidental torsional effects as described in section 2.1.5.5.

All the computer analysis were performed with the ETABs software (CSI 2002. ETABS Integrated Building Design Software, Computers and Structures Inc. Berkley).

4.3.2.1 Structural Model

The EC 8 recommends using a spatial model as the preference method for all type of buildings(*Clause 4.3.1of EN 1998-1:2004*). On account of that, for the test building a three dimensional (spatial) model was developed. The computer model of this building was created in a similar way as described in section 4.1.2.1, in case of building A.

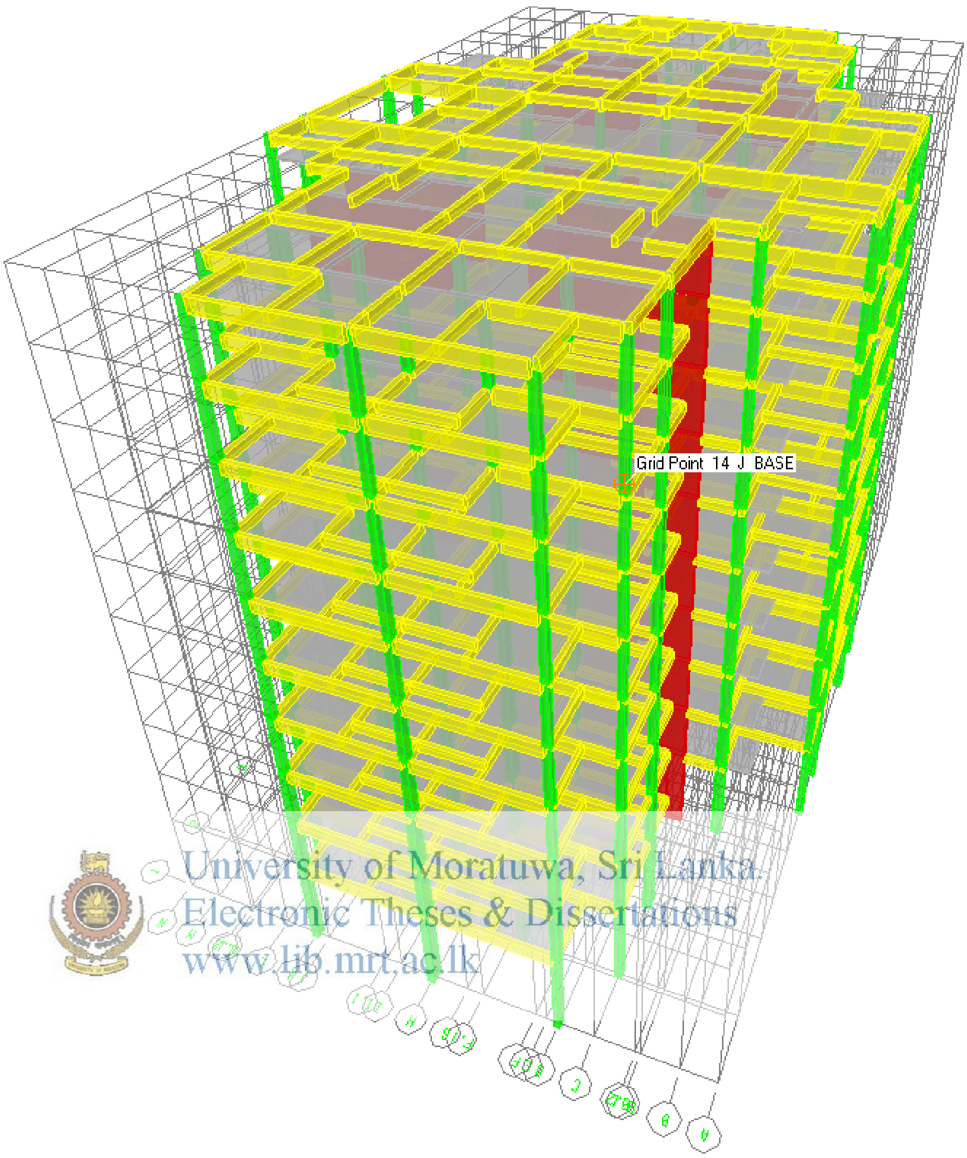

Figure EC-2 : Three dimensional (spatial) model of the building C

4.3.2.2 Lateral force method of analysis

As described in section 2.1.5.4.1, the method of analysis has been carried out in three main steps as follows.

a) Estimating the self-weight and seismic masses of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces and moments

4.3.2.2.1 Estimation of seismic mass of the building

As described in section 2.1.5.1, the seismic mass of the building was taken as the following combination of dead load and the variable loads as,

$$\sum G_{k,j} + \sum \psi_{E,i} Q_{k,I}$$

Table EC-1 : Total seismic mass of building C

Storey	ψ_2 (Table EN-7)	ψ (Table EN-9)	$G_{k,j}$ (t) (Table C-3)	$Q_{k,I}$ (t) (Table C-4)	Seismic mass (t)	Total Seismic mass (t)
Roof	0	1	551	146	551	551
Storey 9	0.3	0.8	722	153	759	759
Storey 8	0.3	0.8	745	153	782	782
Storey 7	0.3	0.8	751	153	788	788
Storey 4-6	0.3	0.8	767	153	804	2412
Storey 3	0.3	0.8	774	153	811	811
Storey 2	0.3	0.8	781	153	818	818
Storey 1	0.3	0.8	820	153	857	857
Total seismic mass of the building						7,778

4.3.2.2.2 Calculating seismic base shear

As described in section 2.1.5.4.1, the seismic base shear force for each horizontal direction was determined by the following equation,

$$F_b = S_d(T_1).m.\lambda$$

T_1: The fundamental period of the building – Refer table C5

$S_d(T_1)$: The value of the ordinate of the design response spectrum, corresponding to the fundamental period T_1 of the building for different soil conditions – Refer figure EC-1

m: The seismic mass of the building - Refer table EC-1

λ : The correction factor, λ can be determined according to clause 4.3.3.2.2 of EN 1998-1: 2004. The values of λ for three different soil conditions are shown in table EC-2.

The base shear force for each horizontal directions for three soil conditions are shown in Table EC-3.

Table EC-2 : Correction factor, λ for building C

Soil Type	T_c	$2T_c$	T_x	T_y	λ_x	λ_y
Soft	0.67	1.34	3.05	1.01	1.00	0.85
Medium	0.55	1.10	3.05	1.01	1.00	0.85
Hard	0.40	0.80	3.05	1.01	1.00	1.00

Table EC-3 : Seismic base shear of building C

Soil Type	Fundamental Period, T_1 (S)		$S_d(T_1)$		m (t)	λ		F_b(kN)	
	X	Y	X	Y		X	Y	X	Y
Soft	3.05	1.01	0.4076	1.2199	7,778	1.00	0.85	3170	8065
Medium	3.05	1.01	0.3340	0.9933	7,778	1.00	0.85	2597	6566
Hard	3.05	1.02	0.2472	0.7299	7,778	1.00	1.00	1922	5678

4.3.2.2.3 Distribution of lateral forces

The seismic base shear (F_b) was distributed at each storey level by using the following expression as shown in section 2.1.5.4.1(C),

$$F_i = F_b \cdot \frac{z_i \cdot m_i}{\sum z_j \cdot m_j}$$

Distribution of seismic base shear at each storey level is shown in Table EC-4.

Table EC-4 : Distribution of seismic base shear at each storey level - Building C

Storey	Height (z_i) (m)	Mass (m_i) (t)	$Z_i.m_i$ (tm)	Fi(kN) Soft		Medium		Hard	
				F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}
Roof	31.46	551	17335	406	1034	333	842	246	728
Storey 9	28.48	759	21617	507	1289	415	1050	307	907
Storey 8	25.5	782	19941	467	1189	383	968	284	837
Storey 7	22.51	788	17738	416	1058	341	861	252	745
Storey 6	19.52	804	15695	368	936	301	762	223	659
Storey 5	16.54	804	13299	312	793	255	646	189	558
Storey 4	13.56	804	10903	256	650	209	529	155	458
Storey 3	10.57	811	8573	201	511	165	416	122	360
Storey 2	7.58	818	6201	145	370	119	301	88	260
Storey 1	4.6	857	3943	92	235	76	191	56	166
Total (?)				3170	8065	2597	6566	1922	5678

4.3.2.3 Modal response spectrum analysis

4.3.2.3.1 General rules

The general rules recommended for this type of analysis, as described in clause 4.3.3.3 of EN 11998-1:2004 were followed in the case of the test building in a similar way as in building A, which is described in section 4.1.2.3.1.

4.3.2.3.2 Periods and effective masses

In the modal response spectrum analysis, 15 modes of vibration were taken in to account as the sum of the modal masses in each horizontal directions to exceeds 90% of the total mass of the structure.

The basic properties of the models are summarized in Table EC-5.

Table EC-5 : Periods and effective modal mass participation of building C (Modal response spectrum analysis)

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	3.05	93.39	0.00
2	1.22	0.01	0.14
3	1.01	0.00	69.06
4	0.94	4.81	0.00
5	0.50	0.89	0.00
6	0.32	0.32	0.00
7	0.27	0.00	0.02
8	0.23	0.14	0.00
9	0.21	0.00	19.77
10	0.17	0.09	0.00
11	0.13	0.04	0.00
12	0.11	0.02	0.00
13	0.11	0.00	0.00
14	0.09	0.02	0.00
15	0.09	0.00	6.41
		99.73%	95.40%

4.3.2.3.3 Torsional effects

As described in section 2.1.5.5, the accidental torsional effect was considered by means of torsional moments ($M_{axi}$and M_{ayi}) applying about the vertical axis at each storey, i. Tthe envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) were added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey level is shown in Table EC-6.

Table EC-6 : Torsional moments at each horizontal direction

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	41.3	25.6	2.06	1.28	406	1034	333	842	246	728	520	2130	426	1735	315	1500
Storey 9	41.3	25.6	2.06	1.28	507	1289	415	1050	307	907	649	2655	531	2163	393	1868
Storey 8	41.3	25.6	2.06	1.28	467	1189	383	968	284	837	598	2449	490	1994	364	1724
Storey 7	41.3	25.6	2.06	1.28	416	1058	341	861	252	745	532	2179	436	1774	323	1535
Storey 6	41.3	25.6	2.06	1.28	368	936	301	762	223	659	471	1928	385	1570	285	1358
Storey 5	41.3	25.6	2.06	1.28	312	793	255	646	189	558	399	1634	326	1331	242	1149
Storey 4	41.3	25.6	2.06	1.28	256	650	209	529	155	458	328	1339	268	1090	198	943
Storey 3	41.3	25.6	2.06	1.28	201	511	165	416	122	360	257	1053	211	857	156	742
Storey 2	41.3	25.6	2.06	1.28	145	370	119	301	88	260	186	762	152	620	113	536
Storey 1	41.3	25.6	2.06	1.28	92	235	76	191	56	166	118	484	97	393	72	342

4.3.2.3.4. Storey shear and displacement

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.1.5.6.

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table EC-7 and EC-8 only.

Table EC-7 : Storey shear forces of building C (Modal response spectrum analysis Method)

Storey	Storey Shear (kN)					
	Soft		Medium		Hard	
	X	Y	X	Y	X	Y
Roof	535	1707	456	1522	355	1333
Storey 9	1106	3319	924	2885	697	2428
Storey 8	1574	4497	1296	3805	964	3047
Storey 7	1963	5427	1608	4491	1193	3432
Storey 6	2309	6226	1893	5094	1405	3792
Storey 5	2618	6935	2151	5673	1597	4217
Storey 4	2900	7567	2384	6235	1771	4716
Storey 3	3166	8119	2598	6767	1930	5252
Storey 2	3426	8546	2807	7203	2080	5724
Storey 1	3666	8789	3004	7461	2225	6012

Table EC-8 : Design displacement (d_s) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_e(m)						q_d	d_s(m)					
	Soft		Medium		Hard			Soft		Medium		Hard	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.1194	0.0490	0.0974	0.0402	0.0725	0.0300	2.00	0.2388	0.0980	0.1948	0.0804	0.1450	0.0600
Storey 9	0.1172	0.0432	0.0960	0.0355	0.0712	0.0265	2.00	0.2344	0.0864	0.1920	0.0710	0.1424	0.0530
Storey 8	0.1129	0.0373	0.0924	0.0306	0.0685	0.0228	2.00	0.2258	0.0746	0.1848	0.0612	0.1370	0.0456
Storey 7	0.1068	0.0313	0.0875	0.0257	0.0648	0.0191	2.00	0.2136	0.0626	0.1750	0.0514	0.1296	0.0382
Storey 6	0.1004	0.0254	0.0822	0.0208	0.0609	0.0155	2.00	0.2008	0.0508	0.1644	0.0416	0.1218	0.0310
Storey 5	0.0928	0.0197	0.0760	0.0162	0.0563	0.0121	2.00	0.1856	0.0394	0.1520	0.0324	0.1126	0.0242
Storey 4	0.0840	0.0143	0.0688	0.0118	0.0509	0.0088	2.00	0.1680	0.0286	0.1376	0.0236	0.1018	0.0176
Storey 3	0.0739	0.0095	0.0605	0.0078	0.0448	0.0058	2.00	0.1478	0.0190	0.1210	0.0156	0.0896	0.0116
Storey 2	0.0627	0.0054	0.0513	0.0044	0.0380	0.0033	2.00	0.1254	0.0108	0.1026	0.0088	0.0760	0.0066
Storey 1	0.0476	0.0022	0.0390	0.0018	0.0289	0.0014	2.00	0.0952	0.0044	0.0780	0.0036	0.0578	0.0028

4.3.2.3.5. Inter-storey drift

The inter-storey drift (d_r) was evaluated as described in section 2.1.5.6.2, considering the difference of the lateral displacements (d_s) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_r) was then checked for damage limitation requirement given by the following equation ,

$$d_r \nu \leq (\propto).\, h$$

Since the structure is of importance level III, the ν value was selected to 0.4.

All parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in tables EC-9, EC-10 and EC-11 for soft, medium and hard soil conditions respectively.

Table EC-9 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Soft soil conditions

Storey	d_r (m)		h	v	d_r * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0044	0.0116	2.985	0.4	0.0006	0.0016	
Storey 9	0.0086	0.0118	2.985	0.4	0.0012	0.0016	
Storey 8	0.0122	0.0120	2.985	0.4	0.0016	0.0016	
Storey 7	0.0128	0.0118	2.985	0.4	0.0017	0.0016	
Storey 6	0.0152	0.0114	2.985	0.4	0.002	0.0015	0.005 0.0075 0.01
Storey 5	0.0176	0.0108	2.985	0.4	0.0024	0.0014	
Storey 4	0.0202	0.0096	2.985	0.4	0.0027	0.0013	
Storey 3	0.0224	0.0082	2.985	0.4	0.003	0.0011	
Storey 2	0.0302	0.0064	2.985	0.4	0.004	0.0009	
Storey 1	0.0952	0.0044	4.6	0.4	0.0083	0.0004	

Table EC-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Medium soil conditions

Storey	d_r(m)		h	v	d_r * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0028	0.0094	2.985	0.4	0.0004	0.0013	
Storey 9	0.0072	0.0098	2.985	0.4	0.001	0.0013	
Storey 8	0.0098	0.0098	2.985	0.4	0.0013	0.0013	
Storey 7	0.0106	0.0098	2.985	0.4	0.0014	0.0013	
Storey 6	0.0124	0.0092	2.985	0.4	0.0017	0.0012	0.005 0.0075 0.01
Storey 5	0.0144	0.0088	2.985	0.4	0.0019	0.0012	
Storey 4	0.0166	0.0080	2.985	0.4	0.0022	0.0011	
Storey 3	0.0184	0.0068	2.985	0.4	0.0025	0.0009	
Storey 2	0.0246	0.0052	2.985	0.4	0.0033	0.0007	
Storey 1	0.0780	0.0036	4.6	0.4	0.0068	0.0003	

Table EC-11 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Hard soil conditions

Storey	d_r (m)		h	v	d_r * v / h		α
	X-dir	Y-dir	(m)		X-dir	Y-dir	
Roof	0.0026	0.0070	2.985	0.4	0.0003	0.0009	
Storey 9	0.0054	0.0074	2.985	0.4	0.0007	0.001	
Storey 8	0.0074	0.0074	2.985	0.4	0.001	0.001	
Storey 7	0.0078	0.0072	2.985	0.4	0.001	0.001	
Storey 6	0.0092	0.0068	2.985	0.4	0.0012	0.0009	0.005 0.0075 0.01
Storey 5	0.0108	0.0066	2.985	0.4	0.0014	0.0009	
Storey 4	0.0122	0.0060	2.985	0.4	0.0016	0.0008	
Storey 3	0.0136	0.0050	2.985	0.4	0.0018	0.0007	
Storey 2	0.0182	0.0038	2.985	0.4	0.0024	0.0005	
Storey 1	0.0578	0.0028	4.6	0.4	0.005	0.0002	

4.3.2.3.6 P-Δ effects

As described in section 2.1.5.7, the P-Δ effects was checked according to the equation given as,

$$\theta = \frac{P_{tot}.d_r}{V_{tot}.h} \leq 0.10$$

Where,

P_{tot}: Is the total gravity load, including appropriate amount of imposed load at and above the storey considered in the seismic design situation – From table EC-1.

d_r: Is the inter-storey drift – From table EC-9, EC-10, EC-11 as appropriately for particular soil type.

V_{tot}: Is the total seismic storey shear from response spectrum analysis.

h : Floor to floor height.

The calculation of the inter-storey drift sensitivity coefficient from modal response spectrum analysis are shown in Table EC-12, EC-13 and EC-14 for soft, medium and hard soil conditions respectively.

Table EC-12 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Soft soil conditions.

Storey	P_{tot} (kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	5,405	0.0044	0.0116	535	1707	2.985	0.015	0.012
Storey 9	12,851	0.0086	0.0118	1106	3319	2.985	0.033	0.015
Storey 8	20,523	0.0122	0.0120	1574	4497	2.985	0.053	0.018
Storey 7	28,253	0.0128	0.0118	1963	5427	2.985	0.062	0.021
Storey 6	36,140	0.0152	0.0114	2309	6226	2.985	0.08	0.022
Storey 5	44,027	0.0176	0.0108	2618	6935	2.985	0.099	0.023
Storey 4	51,915	0.0202	0.0096	2900	7567	2.985	0.121	0.022
Storey 3	59,870	0.0224	0.0082	3166	8119	2.985	0.142	0.02
Storey 2	67,895	0.0302	0.0064	3426	8546	2.985	0.2	0.017
Storey 1	76,302	0.0952	0.0044	3666	8789	4.6	0.431	0.008

Table EC-13 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Medium soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	5,405	0.0028	0.0094	456	1522	2.985	0.011	0.011
Storey 9	12,851	0.0072	0.0098	924	2885	2.985	0.034	0.015
Storey 8	20,523	0.0098	0.0098	1296	3805	2.985	0.052	0.018
Storey 7	28,253	0.0106	0.0098	1608	4491	2.985	0.062	0.021
Storey 6	36,140	0.0124	0.0092	1893	5094	2.985	0.079	0.022
Storey 5	44,027	0.0144	0.0088	2151	5673	2.985	0.099	0.023
Storey 4	51,915	0.0166	0.0080	2384	6235	2.985	0.121	0.022
Storey 3	59,870	0.0184	0.0068	2598	6767	2.985	0.142	0.02
Storey 2	67,895	0.0246	0.0052	2807	7203	2.985	0.199	0.016
Storey 1	76,302	0.0780	0.0036	3004	7461	4.6	0.431	0.008

Table EC-14 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Hard soil conditions.

Storey	P_{tot}(kN)	d_r (m)		V_{tot} (kN)		h	θ	
		X	Y	X	Y	(m)	X	Y
Roof	5,405	0.0026	0.0070	355	1333	2.985	0.013	0.01
Storey 9	12,851	0.0054	0.0074	697	2428	2.985	0.033	0.013
Storey 8	20,523	0.0074	0.0074	964	3047	2.985	0.053	0.017
Storey 7	28,253	0.0078	0.0072	1193	3432	2.985	0.062	0.02
Storey 6	36,140	0.0092	0.0068	1405	3792	2.985	0.079	0.022
Storey 5	44,027	0.0108	0.0066	1597	4217	2.985	0.1	0.023
Storey 4	51,915	0.0122	0.0060	1771	4716	2.985	0.12	0.022
Storey 3	59,870	0.0136	0.0050	1930	5252	2.985	0.141	0.019
Storey 2	67,895	0.0182	0.0038	2080	5724	2.985	0.199	0.015
Storey 1	76,302	0.0578	0.0028	2225	6012	4.6	0.431	0.008

5.0 ANALYSIS ACCORDING TO AUSTRALIAN CODE { AS 1170.4-2007}

5.1 BUILDING "A"

The selected building is an eighteen storied reinforced concrete apartment building, which includes aground floor and seventeen above floors. The basic descriptions and calculations of this structure are described in appendix A.

5.1.1 Design seismic action

Classification of building

This is an apartment building having more than 15 storeys. Therefore the building is categorized as Importance level 3 (*Table AS-2*)

Reference probability of exceedance

Annual probability of the design event for safety for earthquake condition for Importance level 3 =1/1000 (*Table AS-1*)

Probability factor, k_p

For annual probability of exceedance = 1/1000, k_p=1.3(*Table AS-4*)

Hazard factor, *Z*

The hazard factor, *Z* for different locations in Australia is given in table 3.2 of AS 1170.4-2007. However, for Sri Lankan conditions, it was considered to be 0.1 throughout the country.

Sub-soil class

For very soft soil conditions, sub-soil class = E_e

For shallow soil condition, sub-soil class = C_e

For rock condition, sub-soil class = B_e

Selection of earthquake design category

Importance level: 3

Structure height, h_n : 71.2m

$k_p Z$ = 1.3 x 0.1 = 0.13

Therefore, according to table *AS*-3, the building shall be designed for earthquake design categories based on sub-soil classes as follows III (EDC III).

Sub-soil class E_e : Earthquake Design Category III (EDCIII)

Sub-soil class C_e : Earthquake Design Category III (EDCIII)

Sub-soil class B_e : Earthquake Design Category III (EDCIII)

Horizontal design response spectrum $C_d(T)$

$C_d(T)$ = $C(T)S_p/\mu$ (Equation 6.2(4) of AS 1170.4:2007)

= $K_p Z C_h(T) S_p/\mu$ (Equation 6.2(5) of AS 1170.4:2007)

For a structure consists of ordinary moment-resisting frames in combination with a limited ductile shear walls,

S_p/μ = 0.38 (*Table AS-6*)

$C_d(T)$ = 0.13 X 0.38 X $C_h(T)$

$C_d(T)$ = 0.0494 $C_h(T)$

5.1.2 Method of analysis

The code recommends to use dynamic analysis to calculate earthquake forces (Clause 5.5.2.2 of AS 1170.4-2007) without considering vertical earthquake actions, except parts and components. Therefore, in this research, a modal response spectrum analysis was performed on a three dimensional structural model of the building. However, equivalent static analysis was also performed in order to obtain the horizontal force acting on each storey, which has been used to determine accidental torsional effects as described in section 6.6 of AS 1170.4-2007.

5.1.2.1 Structural Model

A three dimensional mathematical model was used in this analysis since it could represent the special distribution of the mass and the stiffness of the structure adequately.

In this study, the building was considered to have no significant structural effect from the masonry infill walls on its behavior when subjected to seismic load. The reinforced concrete frame wall system was considered as the only lateral load resisting system in the building and therefore, the presence of masonry infill walls were not considered in making the model. However, their weight was considered in the calculation of seismic weight of the building.

It was required that the model should fulfill all the requirements specified in the code. The basic characteristics of the model of the test building considering the requirements in the code are as follows.

- Column and beam elements were modeled as line elements whereas the floor slabs and concrete walls were modeled as shell elements.
- The elements were modeled with the actual sizes such that they adequately represent the distribution of stiffness and mass of the building.
- Even though it is not specifically discussed about the influence of cracked sections in AS 1170.4:2007, this influence was reflected in the model by multiplying the moment of inertia and shear area of the un-cracked sections by 0.5 in order to take the elastic flexural and shear properties one-half of those corresponding to un-cracked elements**.** Torsional stiffness of the cracked sections was set equal to 10% of the torsional stiffness of the un-cracked sections.
- Frames were connected by means of rigid diaphragms in horizontal plane at each floor level.
- The accidental torsional effect was considered by applying torsional moments about vertical axis as described in Clause 6.6 of AS 1170.4-2007.

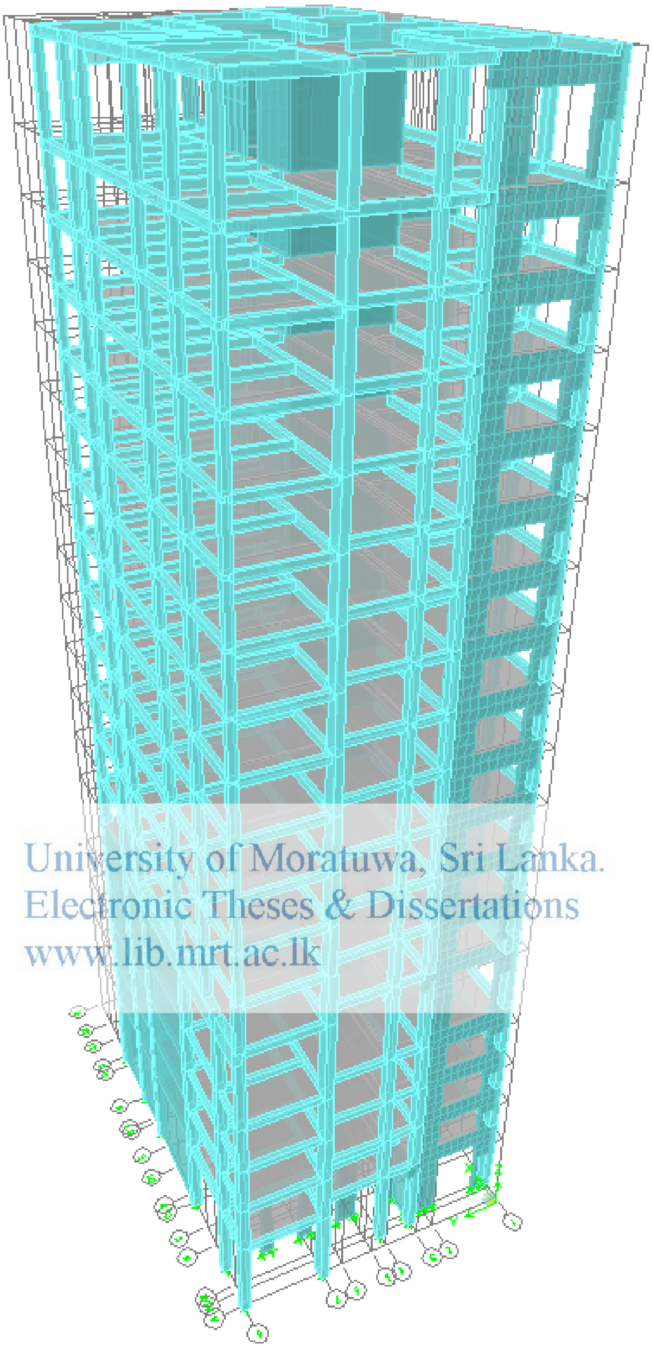

Figure AA-1: Three dimensional (spatial) model of building A

5.1.2.2. Equivalent static analysis

Equivalent static analysis can be carried out in three main steps as follows.

a). Estimating the self-weight and seismic weight of the building b). Calculating the seismic base shear in relevant directions

c). Distribution of lateral forces at different floor levels.

5.1.2.2.1 Estimation of seismic weight of the building

As described in section 2.2.4.1 the seismic weight of the building can be found by following combination of dead load and the variable loads as,

$$W_i = \sum G_i + \sum \psi_c \, . Q_{,i}$$

Table AA-1 : Total seismic weight of building A

Storey	ψ_c	$G_{k,j}$	$Q_{k,I}$	Seismic weight	Total Seismic weight
	(Clause 6.2.2 of AS 1170.4-2007)	(kN)	(kN)	(kN)	(kN)
Roof	0.3	4,911	811	5,154	5,154
Storey 17	0.3	6,340	811	6,583	6,583
Storey 7-16	0.3	5,952	811	6,195	61,950
Storey 6	0.3	6,032	811	6,275	6,275
Storey 5	0.3	7,652	811	7,895	7,895
Storey 4	0.3	6,279	1,227	6,647	6,647
Storey 3-2	0.3	5,620	1,227	5,988	11,976
Storey 1	0.3	6,372	1,227	6,740	6,740
Total seismic weight of the building					113,220

5.1.2.2.2 Calculation of seismic base shear

The seismic base shear force for each horizontal direction was determined by the expression given in Clause 6.2.1 of AS 1170.4-2007.

$$V = C_d(T_1)W_t$$

$$C_d(T_1) = 0.0494C_h(T_1) \quad \text{(From section 5.1.1)}$$

$$V = 0.0494C_h(T_1)W_t$$

T_1: The fundamental period of the building

From modal analysis - Refer Table A5

From eq.6.2(7) of AS 1170.4-2007 - When k_t= 0.05and

h_n= 71.2 m

T_1= 1.53 S

$C_h(T_1)$: The values of the spectral shape factors are obtained from table 6.4 of AS 1170.4:2007.

W_t : The seismic weight of the building - Refer table AA-1

The base shear forces for each horizontal direction, based on T_1 calculated according to both of above methods are shown in Table AA-2 and AA-3.Base shear forces calculated using $T_{1,}$ obtained from modal analysis were then checked weather they exceed 80% of the base shear values obtained with T_1 calculated using the above equation. Base shear forces of the structure, after the comparison are shown in Table AA-4.

Table AA-2 : Design seismic base shear of building A (T_1 from modal analysis)

Soil type	Fundamental period, T_1 (S) from modal analysis		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)	
	X	Y	X	Y					X	Y
Very soft soil	1.32	1.64	2.38	1.74	1.3	0.1	0.38	113,220	13312	9732
Shallow soil	1.32	1.64	0.96	0.71	1.3	0.1	0.38	113,220	5370	3972
Rock	1.32	1.64	0.68	0.5	1.3	0.1	0.38	113,220	3804	2797

Table AA-3 : Design seismic base shear of building A (T_1 from eq. 6.2(7) of AS 1170.4-2007)

Soil type	Fundamental period, T_1 (S) from eq.6.2(7) of AS 1170.4-2007		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)		80% of V (kN)	
	X	Y	X	Y					X	Y	X	Y
Very soft soil	1.53	1.53	1.99	1.99	1.3	0.1	0.38	113,220	11131	11131	8905	8905
Shallow soil	1.53	1.53	0.81	0.81	1.3	0.1	0.38	113,220	4531	4531	3625	3625
Rock	1.53	1.53	0.58	0.58	1.3	0.1	0.38	113,220	3244	3244	2595	2595

Table AA-4 : Design seismic base shear of building A

Soil type	Base Shear, V (kN)	
	X	Y
Very soft soil	13312	9732
Shallow soil	5370	3972
Rock	3804	2797

5.1.2.2.3 Distribution of lateral forces

The seismic base shear (V) was then distributed at each storey level by using the following expression as shown in 2.2.4.3.1.3,

$F_i = k_{F,i}V$ (Refer AS 1170.4: 2007/eq 6.3(1))

$$= \frac{W_i {h_i}^k}{\sum_{j=1}^{n} W_j {h_j}^k} [K_p Z C_h(T_1) \frac{S_p}{\mu} /] W_t$$ (Refer AS 1170.4: 2007/eq 6.2(2)

The values for k in X direction (kx) and in Y direction (ky) were calculated according to Clause 6.3 of AS 1170.4-2002, as follows.

k=exponent depend on the fundamental period of the structure (T_1), which is taken as-

1.0 when $T_1 \leq 0.5$;

2.0 when $T_1 \geq 2.5$; or

linearly interpolated between 1.0 and 2.0 for $0.5 < T_1 < 2.5$

The distribution of seismic base shear at each storey level is shown in Table AA-5

Table AA-5 : Distribution of seismic base shear at each storey level

Storey	Height (hi) (m)	k_x	k_y	h_i^{kx}	h_i^{ky}	Weight (Wi) (kN)	$W_i h_i^{kx}$	$W_i h_i^{ky}$	F_i(kN) Very soft soil F_{ix}	Very soft soil F_{iy}	Shallow soil F_{ix}	Shallow soil F_{iy}	Rock F_{ix}	Rock F_{iy}
Roof	71.2	1.44	1.57	465	810	5,154	2,396,610	4,174,740	1,377	1,060	556	433	394	305
Storey	66	1.44	1.57	417	719	6,583	2,745,111	4,733,177	1,577	1,202	636	491	451	345
Storey	62.4	1.44	1.57	385	658	6,195	2,385,075	4,076,310	1,371	1,035	553	422	392	297
Storey	58.8	1.44	1.57	353	600	6,195	2,186,835	3,717,000	1,257	944	507	385	359	271
Storey	55.2	1.44	1.57	322	543	6,275	2,020,550	3,407,325	1,161	865	468	353	332	249
Storey	51.6	1.44	1.57	293	488	6,195	1,815,135	3,023,160	1,043	768	421	313	298	221
Storey	48	1.44	1.57	264	436	6,195	1,635,480	2,701,020	940	686	379	280	269	197
Storey	44.4	1.44	1.57	236	386	6,195	1,462,020	2,391,270	840	607	339	248	240	175
Storey	40.8	1.44	1.57	209	338	6,195	1,294,755	2,093,910	744	532	300	217	213	153
Storey 9	37.2	1.44	1.57	183	292	6,195	1,133,685	1,808,940	651	459	263	187	186	132
Storey 8	33.6	1.44	1.57	158	249	6,195	978,810	1,542,555	562	392	227	160	161	113
Storey 7	30	1.44	1.57	134	208	6,195	830,130	1,288,560	477	327	192	134	136	94
Storey 6	26.4	1.44	1.57	111	171	6,275	696,525	1,073,025	400	272	161	111	114	78
Storey 5	22.8	1.44	1.57	90	136	7,895	710,550	1,073,720	408	273	165	111	117	78
Storey 4	16.8	1.44	1.57	58	84	6,647	385,526	558,348	222	142	89	58	63	41
Storey 3	13.2	1.44	1.57	41	57	5,988	245,508	341,316	141	87	57	35	40	25
Storey 2	9.6	1.44	1.57	26	35	5,988	155,688	209,580	89	53	36	22	26	15
Storey 1	6	1.44	1.57	13	17	6,740	87,620	114,580	50	29	20	12	14	8
Total							23,165,613	38,328,536	13,310	9,733	5,369	3,972	3,805	2,797

5.1.2.3 Modal response spectrum analysis

5.1.2.3.1. General rules

The general rules recommended for this type of analysis were followed in the case of the test building and are given as follows.

- Modal response spectrum analysis was performed independently for the ground excitation in two horizontal directions.
- For the combination of different modes, the "Complete Quadratic Combination (CQC) rule was used.
- The results of the modal analysis in both directions were combined by the SRSS rule.
- The load combinations were considered according to Clause 4.2.2 of AS 1170.0; 2002.
- The accidental torsional effect was considered by means of torsional moments about the vertical axis according to Clauses 7.4.4.1 and 6.6 of AS 1170.4-2007.

5.1.2.3.2 Periods and effective masses

In modal response spectrum analysis, adequate modes of vibrations has been taken in to account as described in Clause 7.4.2 of AS1170.4-2007.

The basic modal properties are summarized in Table AA-6.

Table AA-6 : Periods and effective modal mass participation of building A (Modal response spectrum analysis

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	1.64	15.25	48.57
2	1.32	42.46	16.93
3	0.71	0.11	0.10
4	0.36	4.77	14.43
5	0.31	15.12	6.41
6	0.23	1.11	0.18
7	0.16	2.61	1.07
8	0.14	6.19	0.71
9	0.13	0.19	3.42
10	0.11	0.28	0.10
11	0.09	3.33	0.20
12	0.08	0.04	3.18
13	0.08	0.07	0.33
14	0.07	0.09	0.00
15	0.07	0.00	0.00
		91.62%	95.63%

5.1.2.3.3 Torsional effects

As described in section 2.2.4.3.1.4, the accidental torsional effect has been considered by means of torsional moments ($M_{axi}$and M_{ayi}), applying about the vertical axis at each storey, i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculations of torsional moments at each storey level are listed in tables AA-7 for very soft soil, shallow soil and rock conditions.

Table AA-7 : Torsional moments - Building A

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Very soft		Shallow		Rock		Very soft		Shallow		Rock	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	28.99	18.88	2.9	1.89	1377	1060	556	433	394	305	2603	3074	1051	1256	**745**	**885**
Storey 17	28.99	18.88	2.9	1.89	1577	1202	636	491	451	345	2981	3486	1202	1424	**852**	**1001**
Storey 16	28.99	18.88	2.9	1.89	1371	1035	553	422	392	297	2591	3002	1045	1224	**741**	**861**
Storey 15	28.99	18.88	2.9	1.89	1257	944	507	385	359	271	2376	2738	958	1117	**679**	**786**
Storey 14	28.99	18.88	2.9	1.89	1161	865	468	353	332	249	2194	2509	885	1024	**627**	**722**
Storey 13	28.99	18.88	2.9	1.89	1043	768	421	313	298	221	1971	2227	796	908	**563**	**641**
Storey 12	28.99	18.88	2.9	1.89	940	686	379	280	269	197	1777	1989	716	812	**508**	**571**
Storey 11	28.99	18.88	2.9	1.89	840	607	339	248	240	175	1588	1760	641	719	**454**	**508**
Storey 10	28.99	18.88	2.9	1.89	744	532	300	217	213	153	1406	1543	567	629	**403**	**444**
Storey 9	28.99	18.88	2.9	1.89	651	459	263	187	186	132	1230	1331	497	542	**352**	**383**
Storey 8	28.99	18.88	2.9	1.89	562	392	227	160	161	113	1062	1137	429	464	**304**	**328**
Storey 7	28.99	18.88	2.9	1.89	477	327	192	134	136	94	902	948	363	389	**257**	**273**
Storey 6	28.99	18.88	2.9	1.89	400	272	161	111	114	78	756	789	304	322	**215**	**226**
Storey 5	28.99	18.88	2.9	1.89	408	273	165	111	117	78	771	792	312	322	**221**	**226**
Storey 4	28.99	18.88	2.9	1.89	222	142	89	58	63	41	420	412	168	168	**119**	**119**
Storey 3	28.99	18.88	2.9	1.89	141	87	57	35	40	25	266	252	108	102	**76**	**73**
Storey 2	28.99	18.88	2.9	1.89	89	53	36	22	26	15	168	154	68	64	**49**	**44**
Storey 1	28.99	18.88	2.9	1.89	50	29	20	12	14	8	95	84	38	35	**26**	**23**

5.1.2.3.4 Storey shear and displacements

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.2.4.3.1.5

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table AA-8 and AA-9 respectively.

Table AA-8: Storey shear forces of building A (Modal response spectrum analysis method)

Storey	Storey Shear (kN)					
	Very soft		Shallow		Rock	
	X	Y	X	Y	X	Y
Roof	923	804	689	595	534	452
Storey 17	1589	1381	1080	969	832	733
Storey 16	2064	1851	1320	1227	1008	922
Storey 15	2474	2232	1446	1385	1093	1034
Storey 14	2816	2543	1500	1465	1120	1086
Storey 13	3112	2804	1517	1492	1118	1097
Storey 12	3377	3030	1526	1492	1108	1089
Storey 11	3621	3234	1560	1484	1121	1076
Storey 10	3857	3426	1646	1492	1181	1074
Storey 9	4088	3615	1795	1537	1296	1103
Storey 8	4311	3809	1990	1637	1451	1177
Storey 7	4520	4010	2174	1795	1626	1297
Storey 6	4714	4222	2434	2005	1809	1459
Storey 5	5020	4604	2824	2438	2125	1795
Storey 4	5185	4816	3045	2695	2305	1994
Storey 3	5310	4983	3213	2904	2442	2159
Storey 2	5394	5102	3327	3058	2535	2281
Storey 1	5442	5177	3395	3159	2589	2362

Table AA-9: Design displacement (d_i) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_{ie}(m)							d_i(m)					
	Very soft soil		Shallow soil		Rock		μ/S_p	Very soft soil		Shallow soil		Rock	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.0849	0.0875	0.0413	0.0409	0.0312	0.0304	2.6	0.2207	0.2275	0.1074	0.1063	0.0811	0.0790
Storey 17	0.0765	0.0790	0.0369	0.0372	0.0278	0.0277	2.6	0.1989	0.2054	0.0959	0.0967	0.0723	0.0720
Storey 16	0.0706	0.0736	0.0339	0.0348	0.0255	0.0259	2.6	0.1836	0.1914	0.0881	0.0905	0.0663	0.0673
Storey 15	0.0646	0.0682	0.0309	0.0323	0.0232	0.0242	2.6	0.1680	0.1773	0.0803	0.0840	0.0603	0.0629
Storey 14	0.0586	0.0627	0.0279	0.0299	0.0209	0.0224	2.6	0.1524	0.1630	0.0725	0.0777	0.0543	0.0582
Storey 13	0.0526	0.0573	0.0249	0.0274	0.0186	0.0206	2.6	0.1368	0.1490	0.0647	0.0712	0.0484	0.0536
Storey 12	0.0465	0.0518	0.0220	0.0250	0.0164	0.0188	2.6	0.1209	0.1347	0.0572	0.0650	0.0426	0.0489
Storey 11	0.0406	0.0464	0.0191	0.0225	0.0143	0.0169	2.6	0.1056	0.1206	0.0497	0.0585	0.0372	0.0439
Storey 10	0.0348	0.0411	0.0163	0.0201	0.0122	0.0151	2.6	0.0905	0.1069	0.0424	0.0523	0.0317	0.0393
Storey 9	0.0291	0.0360	0.0137	0.0176	0.0102	0.0133	2.6	0.0757	0.0936	0.0356	0.0458	0.0265	0.0346
Storey 8	0.0238	0.0309	0.0111	0.0153	0.0083	0.0115	2.6	0.0619	0.0803	0.0289	0.0398	0.0216	0.0299
Storey 7	0.0188	0.0261	0.0088	0.0129	0.0065	0.0097	2.6	0.0489	0.0679	0.0229	0.0335	0.0169	0.0252
Storey 6	0.0142	0.0215	0.0066	0.0106	0.0048	0.0080	2.6	0.0369	0.0559	0.0172	0.0276	0.0125	0.0208
Storey 5	0.0109	0.0175	0.0050	0.0085	0.0036	0.0063	2.6	0.0283	0.0455	0.0130	0.0221	0.0094	0.0164
Storey 4	0.0063	0.0105	0.0029	0.0053	0.0021	0.0040	2.6	0.0164	0.0273	0.0075	0.0138	0.0055	0.0104
Storey 3	0.0042	0.0070	0.0020	0.0036	0.0014	0.0027	2.6	0.0109	0.0182	0.0052	0.0094	0.0036	0.0070
Storey 2	0.0024	0.0041	0.0012	0.0022	0.0009	0.0016	2.6	0.0062	0.0107	0.0031	0.0057	0.0023	0.0042
Storey 1	0.0011	0.0018	0.0005	0.0010	0.0004	0.0008	2.6	0.0029	0.0047	0.0013	0.0026	0.0010	0.0021

5.1.2.3.5 Storey drifts

The design drift(d_{st}) at each floor levels of the structure were evaluated as described in section 2.2.4.3.1.5 considering the difference of the deflections (d_i) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_{st}) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 1.5% of the storey height(h) according to clause 5.5.4 of AS 1170.4-2007.

All parameters for the verification of the damage limitation requirement obtained by response spectrum analysis for different soil conditions are listed in Table AA-10.

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Table AA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building A

Storey	dst (m)						h (m)	1.5% h
	Very soft soil		Shallow soil		Rock			
	x	y	x	y	x	y		
Roof	0.02184	0.0221	0.0114	0.0096	0.0088	0.0070	5.2	0.078
Storey 17	0.01534	0.01404	0.0078	0.0062	0.0060	0.0047	3.6	0.054
Storey 16	0.0156	0.01404	0.0078	0.0065	0.0060	0.0044	3.6	0.054
Storey 15	0.0156	0.0143	0.0078	0.0062	0.0060	0.0047	3.6	0.054
Storey 14	0.0156	0.01404	0.0078	0.0065	0.0060	0.0047	3.6	0.054
Storey 13	0.01586	0.0143	0.0075	0.0062	0.0057	0.0047	3.6	0.054
Storey 12	0.01534	0.01404	0.0075	0.0065	0.0055	0.0049	3.6	0.054
Storey 11	0.01508	0.01378	0.0073	0.0062	0.0055	0.0047	3.6	0.054
Storey 10	0.01482	0.01326	0.0068	0.0065	0.0052	0.0047	3.6	0.054
Storey 9	0.01378	0.01326	0.0068	0.0060	0.0049	0.0047	3.6	0.054
Storey 8	0.013	0.01248	0.0060	0.0062	0.0047	0.0047	3.6	0.054
Storey 7	0.01196	0.01196	0.0057	0.0060	0.0044	0.0044	3.6	0.054
Storey 6	0.00858	0.0104	0.0042	0.0055	0.0031	0.0044	3.6	0.054
Storey 5	0.01196	0.0182	0.0055	0.0083	0.0039	0.0060	6	0.09
Storey 4	0.00546	0.0091	0.0023	0.0044	0.0018	0.0034	3.6	0.054
Storey 3	0.00468	0.00754	0.0021	0.0036	0.0013	0.0029	3.3	0.0495
Storey 2	0.00338	0.00598	0.0018	0.0031	0.0013	0.0021	3.6	0.054
Storey 1	0.00286	0.00468	0.0013	0.0026	0.0010	0.0021	6	0.09

5.1.2.3.6 P-Δ effects

As described in section 2.2.4.3.1.6, the P-Δ effects was checked according to the following equation,

$$\theta = d_{st} \sum_{j=1}^{n} W_j \Big/ \left(h_{si} \mu \sum_{j=1}^{n} F_j \right)$$

Where,

d_{st}: The design storey drift – From table AA-8, as appropriately for particular soil type.

W_j: Seismic weight of the structure or component at level j in kilo Newton – From table AA-1.

h_{si}: Inter-storey height of level i, measured from centre-line to centre-line of the floors.

μ: Structural ductility factor - From table AS-6.

F_j: Horizontal dynamic force at the jth level, obtained from response spectrum analysis - From table AA-8 as appropriately.

The calculation procedure related to inter-storey stability coefficient for three different ground conditions are listed in table AA-11, AA-12 and AA-13.

Table AA-11 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Very soft soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	5,154	0.0218	0.0221	923	804	5.2	2	0.012	0.014
Storey 17	11,737	0.0153	0.0140	1589	1381	3.6	2	0.016	0.017
Storey 16	17,932	0.0156	0.0140	2064	1851	3.6	2	0.019	0.019
Storey 15	24,127	0.0156	0.0143	2474	2232	3.6	2	0.021	0.021
Storey 14	30,322	0.0156	0.0140	2816	2543	3.6	2	0.023	0.023
Storey 13	36,517	0.0159	0.0143	3112	2804	3.6	2	0.026	0.026
Storey 12	42,712	0.0153	0.0140	3377	3030	3.6	2	0.027	0.027
Storey 11	48,907	0.0151	0.0138	3621	3234	3.6	2	0.028	0.029
Storey 10	55,102	0.0148	0.0133	3857	3426	3.6	2	0.029	0.03
Storey 9	61,297	0.0138	0.0133	4088	3615	3.6	2	0.029	0.031
Storey 8	67,492	0.0130	0.0125	4311	3809	3.6	2	0.028	0.031
Storey 7	73,687	0.0120	0.0120	4520	4010	3.6	2	0.027	0.031
Storey 6	79,962	0.0086	0.0104	4714	4222	3.6	2	0.02	0.027
Storey 5	87,857	0.0120	0.0182	5020	4604	6	2	0.017	0.029
Storey 4	94,504	0.0055	0.0091	5185	4816	3.6	2	0.014	0.025
Storey 3	100,492	0.0047	0.0075	5310	4983	3.3	2	0.013	0.023
Storey 2	106,480	0.0034	0.0060	5394	5102	3.6	2	0.009	0.017
Storey 1	113,220	0.0029	0.0047	5442	5177	6	2	0.005	0.009

Table AA-12 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Shallow soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	5,154	0.0114	0.0096	689	595	5.2	2	0.008	0.008
Storey 17	11,737	0.0078	0.0062	1080	969	3.6	2	0.012	0.01
Storey 16	17,932	0.0078	0.0065	1320	1227	3.6	2	0.015	0.013
Storey 15	24,127	0.0078	0.0062	1446	1385	3.6	2	0.018	0.015
Storey 14	30,322	0.0078	0.0065	1500	1465	3.6	2	0.022	0.019
Storey 13	36,517	0.0075	0.0062	1517	1492	3.6	2	0.025	0.021
Storey 12	42,712	0.0075	0.0065	1526	1492	3.6	2	0.029	0.026
Storey 11	48,907	0.0073	0.0062	1560	1484	3.6	2	0.032	0.029
Storey 10	55,102	0.0068	0.0065	1646	1492	3.6	2	0.031	0.033
Storey 9	61,297	0.0068	0.0060	1795	1537	3.6	2	0.032	0.033
Storey 8	67,492	0.0060	0.0062	1990	1637	3.6	2	0.028	0.036
Storey 7	73,687	0.0057	0.0060	2174	1795	3.6	2	0.027	0.034
Storey 6	79,962	0.0042	0.0055	2434	2005	3.6	2	0.019	0.03
Storey 5	87,857	0.0055	0.0083	2824	2438	6	2	0.014	0.025
Storey 4	94,504	0.0023	0.0044	3045	2695	3.6	2	0.01	0.022
Storey 3	100,492	0.0021	0.0036	3213	2904	3.3	2	0.01	0.019
Storey 2	106,480	0.0018	0.0031	3327	3058	3.6	2	0.008	0.015
Storey 1	113,220	0.0013	0.0026	3395	3159	6	2	0.004	0.008

Table AA-13 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Rock conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	5,154	0.0088	0.0070	534	452	5.2	2	0.008	0.008
Storey 17	11,737	0.0060	0.0047	832	733	3.6	2	0.012	0.01
Storey 16	17,932	0.0060	0.0044	1008	922	3.6	2	0.015	0.012
Storey 15	24,127	0.0060	0.0047	1093	1034	3.6	2	0.018	0.015
Storey 14	30,322	0.0060	0.0047	1120	1086	3.6	2	0.022	0.018
Storey 13	36,517	0.0057	0.0047	1118	1097	3.6	2	0.026	0.022
Storey 12	42,712	0.0055	0.0049	1108	1089	3.6	2	0.029	0.027
Storey 11	48,907	0.0055	0.0047	1121	1076	3.6	2	0.033	0.03
Storey 10	55,102	0.0052	0.0047	1181	1074	3.6	2	0.034	0.033
Storey 9	61,297	0.0049	0.0047	1296	1103	3.6	2	0.032	0.036
Storey 8	67,492	0.0047	0.0047	1451	1177	3.6	2	0.03	0.037
Storey 7	73,687	0.0044	0.0044	1626	1297	3.6	2	0.028	0.035
Storey 6	79,962	0.0031	0.0044	1809	1459	3.6	2	0.019	0.034
Storey 5	87,857	0.0039	0.0060	2125	1795	6	2	0.013	0.024
Storey 4	94,504	0.0018	0.0034	2305	1994	3.6	2	0.01	0.022
Storey 3	100,492	0.0013	0.0029	2442	2159	3.3	2	0.008	0.02
Storey 2	106,480	0.0013	0.0021	2535	2281	3.6	2	0.008	0.013
Storey 1	113,220	0.0010	0.0021	2589	2362	6	2	0.004	0.008

5.2 BUILDING "B"

The selected building is a fourteen storied reinforced concrete apartment building, which includes a ground floor and thirteen above floors. The basic descriptions and calculations of this structure are described in appendix B.

5.2.1 Design seismic action

Classification of building

Since this is an apartment building having less than 15 storeys, the building has been categorized as Importance level 2 (*Table AS-2*)

Reference probability of exceedance

Annual probability of the design event for safety for earthquake condition for Importance level 2 =1/500 (*Table AS-1*)

Probability factor, k_p

For annual probability of exceedance = 1/500, k_p=1.0(*Table AS-4*)

Hazard factor, *Z*

The hazard factor, *Z* for different locations in Australia is given in table 3.2 of AS 1170.4-2007. However, for Sri Lankan conditions, it was considered to be 0.1 throughout the country.

Sub-soil class

For very soft soil condition, sub-soil class = E_e

For shallow soil condition, sub-soil class = C_e

For rock condition, sub-soil class = B_e

Selection of earthquake design category

Importance level: 2

Structure height, h_n : 46.3m< 50m

$k_pZ = 1.0 \times 0.1 = 0.1$

Therefore, according to table *AS-3*, the building shall be designed for earthquake design categories based on sub-soil classes as follows.

Sub-soil class E_e : Earthquake Design Category III (EDCIII)

Sub-soil class C_e : Earthquake Design Category II (EDCII)

Sub-soil class B_e : Earthquake Design Category II (EDCII)

Horizontal design response spectrum $C_d(T)$

$C_d(T)$ = $C(T)S_p/\mu$ (Equation 6.2(4) of AS 1170.4:2007)

= $K_pZC_h(T)S_p/\mu$ (Equation 6.2(5) of AS 1170.4:2007)

For a structure consists of ordinary moment-resisting frames in combination with a limited ductile shear walls,

S_p/μ = 0.38 (*Table AS-6*)

$C_d(T) = 0.1 \text{ X } 0.38 \text{ X } C_h(T)$

$C_d(T) = 0.038\, C_h(T)$

5.2.2 Method of analysis

To calculate earthquake forces,the code recommends to use either equivalent static analysis or dynamic analysis for EDC II structures and only dynamic analysis for EDC III structures (Clause 5.4.2.2 and 5.5.2.2 of AS 1170.4-2007). The vertical earthquake actions are not required to be considered, except parts and components. Therefore, in this research, a modal response spectrum analysis was performed on a three dimensional structural model of the building. However, equivalent static analysis was also performed in order to obtain the horizontal force acting on each storey, which has been used to determine accidental torsional effects as described in section 6.6 of AS 1170.4-2007.

5.2.2.1 Structural Model

A three dimensional mathematical model has been used in this analysis since it can represents the special distribution of the mass and the stiffness of the structure adequately. The model was created to fulfill all the requirements specified in the code as described in section 5.1.2.1 in case of building A.

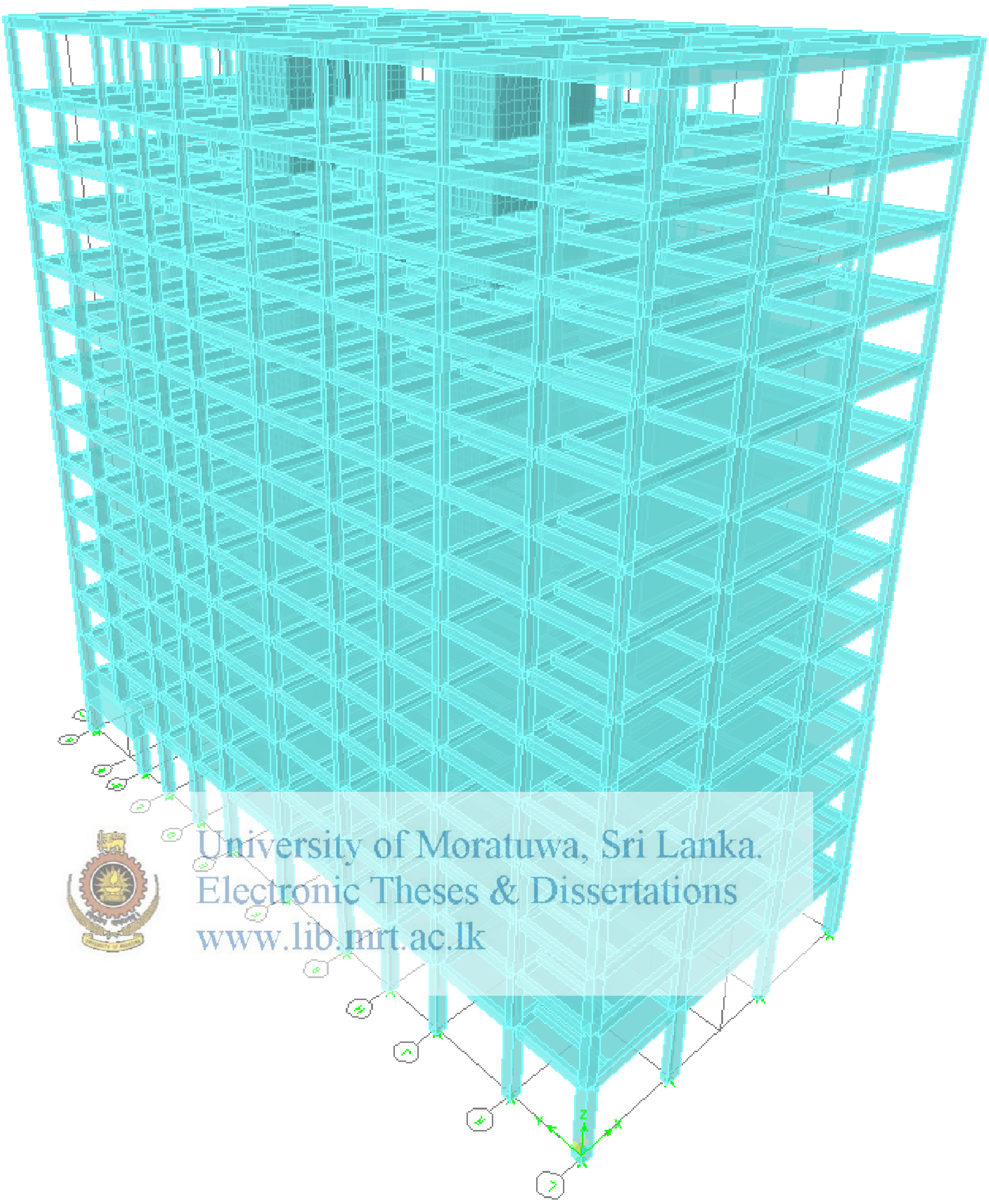

Figure AB-1: Three dimensional (spatial) model of building B

5.2.2.2. Equivalent static analysis

Equivalent static analysis can be carried out in three main steps as follows.

a) Estimating the self-weight and seismic masses of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces and moments

5.2.2.2.1 Estimation of seismic weight of the building

As described in section 2.2.4.1 the seismic weight of the building can be found by following combination of dead load and the variable loads as,

$$W_i = \sum G_i + \sum \psi_c . Q_{,i}$$

Table AB-1 : Total seismic weight of building B

Storey	ψ_c (Clause 6.2.2 of AS 1170.4-2007)	$G_{k,j}$ (kN)	$Q_{k,I}$ (kN)	Seismic weight (kN)	Total Seismic weight (kN)
Roof	0.3	7602	1826	8150	8150
Storey 13	0.3	9884	1826	10432	10432
Storey 12	0.3	9739	1826	10287	10287
Storey 11	0.3	9861	1826	10409	10409
Storey 8-10	0.3	9963	1826	10511	31533
Storey 7	0.3	10003	1826	10551	10551
Storey 5-6	0.3	10034	1826	10582	21164
Storey 4	0.3	10145	183	10200	10200
Storey 2-3	0.3	10239	183	10294	20588
Storey 1	0.3	12023	183	12078	12078
	Total seismic weight of the building				145,392

5.2.2.2.2 Calculation of seismic base shear

The seismic base shear force for each horizontal direction was determined by the expression given in Clause 6.2.1 of AS 1170.4:2002.

$$V = C_d(T_1)W_t$$

$$C_d(T_1) = 0.038C_h(T_1) \text{ (From section 6.2.1)}$$

$$V = 0.0494C_h(T_1)W_t$$

T_1: The fundamental period of vibration of the building

From modal analysis - Refer Table A5

From eq.6.2(7) of AS 1170.4-2007 - When k_t= 0.05and

h_n= 46.3 m

T_1= 1.11 S

$C_h(T_1)$: The values of the spectral shape factors are obtained from table 6.4 of AS 1170.4:2007.

W_t : The seismic weight of the building - Refer table AB-1

The base shear forces for each horizontal direction, based on T_1 calculated according to both of above methods are shown in Table AB-2 and AB-3.Base shear forces calculated using $T_{1,}$ obtained from modal analysis were then checked weather they exceed 80% of the base shear values obtained with T_1 calculated using the above equation. Base shear forces of the structure, after the comparison are shown in Table AB-4.

Table AB-2 : Design seismic base shear of building B (T_1 from modal analysis)

Soil type	Fundamental period, T_1 (S) from modal analysis		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)	
	X	Y	X	Y					X	Y
Very soft soil	1.44	1.59	2.16	1.85	1	0.1	0.38	145,392	11,934	10,222
Shallow soil	1.44	1.59	0.88	0.75	1	0.1	0.38	145,392	4,862	4,144
Rock	1.44	1.59	0.62	0.54	1	0.1	0.38	145,392	3,426	2,984

Table AB-3 : Design seismic base shear of building B (T_1 from eq. 6.2(7) of AS 1170.4-2007)

Soil type	Fundamental period, T_1 (S) from eq.6.2(7) of AS 1170.4-2007		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)		80% of V (kN)	
	X	Y	X	Y					X	Y	X	Y
Very soft soil	1.11	1.11	3.03	3.03	1	0.1	0.38	145,392	16741	16741	13393	13393
Shallow soil	1.11	1.11	1.23	1.23	1	0.1	0.38	145,392	6796	6796	5437	5437
Rock	1.11	1.11	0.87	0.87	1	0.1	0.38	145,392	4807	4807	3846	3846

Table AB-4 : Design seismic base shear of building B

Soil type	Base Shear, V (kN)	
	X	Y
Very soft soil	13393	13393
Shallow soil	5437	5437
Rock	3846	3846

5.2.2.2.3 Distribution of lateral forces

The seismic base shear (V) was then distributed at each storey level by using the following expression as shown in 2.2.4.3.1.3,

$$F_i = k_{F,i} V \qquad \text{(Refer AS 1170.4: 2007/eq 6.3(1))}$$

$$= \frac{W_i {h_i}^k}{\sum_{j=1}^{n} W_j {h_j}^k} \left[K_p Z C_h(T_1) \frac{S_p}{\mu} / \right] W_t \quad \text{(Refer AS 1170.4: 2007/eq 6.2(2)}$$

The values for k in X direction (kx) and in Y direction (ky) were calculated according to Clause 6.3 of AS 1170.4-2002, as described in section 5.1.2.2.3, in case of building A.

The distribution of seismic base shear at each storey level is shown in Table AB-5

Table AB-5:Distribution of seismic base shear - Building B

Storey	Height h_i (m)	k_x	k_y	h_i^{kx}	h_i^{ky}	Weight W_i (kN)	$W_i h_i^{kx}$	$W_i h_i^{ky}$	F_i(kN)					
									Very soft soil		Shallow soil		Rock	
									F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}
Roof	46.3	1.47	1.55	281	382	8,150	2,290,150	3,113,300	1,748	1,805	709	733	502	518
Storey	42.3	1.47	1.55	246	332	10,432	2,566,272	3,463,424	1,958	2,008	795	815	562	577
Storey	39.15	1.47	1.55	219	294	10,287	2,252,853	3,024,378	1,719	1,753	698	712	494	503
Storey	36	1.47	1.55	194	258	10,409	2,019,346	2,685,522	1,541	1,557	626	632	443	447
Storey	32.85	1.47	1.55	170	224	10,511	1,786,870	2,354,464	1,364	1,365	554	554	392	392
Storey 9	29.7	1.47	1.55	146	192	10,511	1,534,606	2,018,112	1,171	1,170	475	475	336	336
Storey 8	26.55	1.47	1.55	124	161	10,511	1,303,364	1,692,271	995	981	404	398	286	282
Storey 7	23.45	1.47	1.55	103	133	10,551	1,086,753	1,403,283	829	813	337	330	238	234
Storey 6	20.25	1.47	1.55	83	106	10,582	878,306	1,121,692	670	650	272	264	192	187
Storey 5	17.1	1.47	1.55	65	81	10,582	687,830	857,142	525	497	213	202	151	143
Storey 4	13.95	1.47	1.55	48	59	10,200	489,600	601,800	374	349	152	142	107	100
Storey 3	10.8	1.47	1.55	33	40	10,294	339,702	411,760	259	239	105	97	74	69
Storey 2	7.65	1.47	1.55	20	23	10,294	205,880	236,762	157	137	64	56	45	39
Storey 1	4.5	1.47	1.55	9	10	12,078	108,702	120,780	83	70	34	28	24	20
Total							17,550,234	23,104,690	13,393	13,394	5,438	5,438	3,846	3,847

5.2.2.3 Modal response spectrum analysis

5.2.2.3.1. General rules

The general rules recommended for this type of analysis were followed in the case of the test building and are given as follows.

- Modal response spectrum analysis was performed independently for the ground excitation in two horizontal directions.
- For the combination of different modes, the "Complete Quadratic Combination (CQC) rule was used.

- The results of the modal analysis in both directions were combined by the SRSS rule.
- The load combinations were considered according to Clause 2.2.2 of AS 1170.0; 2002.
- The accidental torsional effect was considered by means of torsional moments about the vertical axis according to Clauses 7.4.4.1 and 6.6 of AS 1170.4-2007.

5.2.2.3.2 Periods and effective masses

In the modal response spectrum analysis, adequate modes of vibrations were taken in to account described in Clause 7.4.2 of AS1170.4-2007.

The basic modal properties are summarized in Table AB-6.

Table AB-6 :Periods and effective modal mass participation of building B (Modal response spectrum analysis

Mode	T (s)	M_{effUX} (%)	M_{effUY} (%)
1	1.73	0.58	21.24
2	1.59	0.86	46.59
3	1.44	70.86	0.12
4	0.54	0.08	1.17
5	0.42	12.07	2.45
6	0.41	1.75	14.51
7	0.28	0.01	0.36
8	0.20	6.06	0.02
9	0.18	0.08	6.51
10	0.17	0.08	0.37
11	0.12	0.21	0.04
12	0.11	3.18	0.00
13	0.11	0.01	3.29
14	0.09	0.02	0.04
15	0.10	1.92	0.00
		97.77%	96.71%

5.2.2.3.3 Torsional effects

As described in section 2.2.4.3.1.4, the accidental torsional effect has been considered by means of torsional moments ($M_{axi}$and M_{ayi}), applying about the vertical axis at each storey, i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey levels are listed in tables AB-7 for very soft soil, shallow soil and rock conditions respectively.

Table AB-7 : Torsional moments - Building B

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi (kN)						Mi (kNm)					
					Very soft		Shallow		Rock		Very soft		Shallow		Rock	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	20.6	44.3	2.1	4.4	1,748	1,805	709	733	502	518	7692	3791	3120	1540	**2209**	**1088**
Storey 13	20.6	44.3	2.1	4.4	1,958	2,008	795	815	562	577	8616	4217	3498	1712	**2473**	**1212**
Storey 12	20.6	44.3	2.1	4.4	1,719	1,753	698	712	494	503	7564	3682	3072	1496	**2174**	**1057**
Storey 11	20.6	44.3	2.1	4.4	1,541	1,557	626	632	443	447	6781	3270	2755	1328	**1950**	**939**
Storey 10	20.6	44.3	2.1	4.4	1,364	1,365	554	554	392	392	6002	2867	2438	1164	**1725**	**824**
Storey 9	20.6	44.3	2.1	4.4	1,171	1,170	475	475	336	336	5153	2457	2090	998	**1479**	**706**
Storey 8	20.6	44.3	2.1	4.4	995	981	404	398	286	282	4378	2061	1778	836	**1259**	**593**
Storey 7	20.6	44.3	2.1	4.4	829	813	337	330	238	234	3648	1708	1483	693	**1048**	**492**
Storey 6	20.6	44.3	2.1	4.4	670	650	272	264	192	187	2948	1365	1197	555	**845**	**393**
Storey 5	20.6	44.3	2.1	4.4	525	497	213	202	151	143	2310	1044	938	425	**665**	**301**
Storey 4	20.6	44.3	2.1	4.4	374	349	152	142	107	100	1646	733	669	299	**471**	**210**
Storey 3	20.6	44.3	2.1	4.4	259	239	105	97	74	69	1140	502	462	204	**326**	**145**
Storey 2	20.6	44.3	2.1	4.4	157	137	64	56	45	39	691	288	282	118	**198**	**82**
Storey 1	20.6	44.3	2.1	4.4	83	70	34	28	24	20	366	147	150	59	**106**	**42**

5.2.2.3.4 Storey shear and displacements

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.2.4.3.1.5

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table AB-8 and AB-9 respectively.

Table AB-8: Storey shear forces of building B (Modal response spectrum analysis method)

Storey	Storey Shear (kN)					
	Very soft		Shallow		Rock	
	X	Y	X	Y	X	Y
Roof	906	826	630	610	468	450
Storey 13	1627	1429	1008	965	733	700
Storey 12	2193	1841	1228	1127	879	806
Storey 11	2683	2151	1378	1189	979	843
Storey 10	3119	2411	1489	1214	1060	866
Storey 9	3506	2639	1580	1235	1130	890
Storey 8	3855	2856	1668	1274	1199	925
Storey 7	4175	3078	1767	1359	1269	986
Storey 6	4469	3311	1884	1500	1347	1079
Storey 5	4733	3541	2023	1676	1439	1194
Storey 4	4965	3761	2179	1874	1546	1328
Storey 3	5157	3963	2346	2088	1667	1484
Storey 2	5298	4125	2499	2283	1785	1635
Storey 1	5396	4246	2624	2441	1886	1761

Table AB-9: Design displacement (d_i) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_{ie}(m)						μ/Sp	d_i(m)					
	Very soft soil		Shallow soil		Rock			Very soft soil		Shallow soil		Rock	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.0643	0.0662	0.0275	0.0279	0.0200	0.0200	2.6	0.1672	0.1721	0.0715	0.0725	0.0520	0.0520
Storey 13	0.0597	0.0600	0.0253	0.0252	0.0184	0.0181	2.6	0.1552	0.1560	0.0658	0.0655	0.0478	0.0471
Storey 12	0.0559	0.0551	0.0236	0.0230	0.0171	0.0165	2.6	0.1453	0.1433	0.0614	0.0598	0.0445	0.0429
Storey 11	0.0517	0.0499	0.0218	0.0208	0.0158	0.0149	2.6	0.1344	0.1297	0.0567	0.0541	0.0411	0.0387
Storey 10	0.0472	0.0447	0.0198	0.0187	0.0144	0.0134	2.6	0.1227	0.1162	0.0515	0.0486	0.0374	0.0348
Storey 9	0.0424	0.0393	0.0178	0.0165	0.0129	0.0118	2.6	0.1102	0.1022	0.0463	0.0429	0.0335	0.0307
Storey 8	0.0373	0.0340	0.0150	0.0143	0.0113	0.0102	2.6	0.0970	0.0884	0.0390	0.0372	0.0294	0.0265
Storey 7	0.0320	0.0286	0.0135	0.0122	0.0097	0.0087	2.6	0.0832	0.0744	0.0351	0.0317	0.0252	0.0226
Storey 6	0.0265	0.0233	0.0113	0.0100	0.0081	0.0072	2.6	0.0689	0.0606	0.0294	0.0260	0.0211	0.0187
Storey 5	0.0210	0.0182	0.0090	0.0080	0.0065	0.0057	2.6	0.0546	0.0473	0.0234	0.0208	0.0169	0.0148
Storey 4	0.0156	0.0134	0.0068	0.0060	0.0049	0.0042	2.6	0.0406	0.0348	0.0177	0.0156	0.0127	0.0109
Storey 3	0.0106	0.0090	0.0046	0.0041	0.0033	0.0029	2.6	0.0276	0.0234	0.0120	0.0107	0.0086	0.0075
Storey 2	0.0062	0.0053	0.0027	0.0025	0.0019	0.0018	2.6	0.0161	0.0138	0.0070	0.0065	0.0049	0.0047
Storey 1	0.0030	0.0023	0.0013	0.0011	0.0009	0.0008	2.6	0.0078	0.0060	0.0034	0.0029	0.0023	0.0021

5.2.2.3.5 Storey drifts

The design drift(d_{st}) at each floor levels of the structure were evaluated similar way in building A, as described in section 5.1.2.3.5, considering the difference of the deflections (d_i) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_{st}) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 1.5% of the storey height(h) according to clause 5.5.4 of AS 1170.4-2007.

All parameters for the verification of the damage limitation requirement obtained by response spectrum analysis for different soil conditions are listed in Table AB-10.

Table AB-10: Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Building B

Storey	dst (m)						h (m)	1.5% h
	Very soft soil		Shallow soil		Rock			
	x	y	x	y	x	y		
Roof	0.01196	0.01612	0.0057	0.0070	0.0042	0.0049	4	0.06
Storey 13	0.00988	0.01274	0.0044	0.0057	0.0034	0.0042	3.15	0.0473
Storey 12	0.01092	0.01352	0.0047	0.0057	0.0034	0.0042	3.15	0.0473
Storey 11	0.0117	0.01352	0.0052	0.0055	0.0036	0.0039	3.15	0.0473
Storey 10	0.01248	0.01404	0.0052	0.0057	0.0039	0.0042	3.15	0.0473
Storey 9	0.01326	0.01378	0.0073	0.0057	0.0042	0.0042	3.15	0.0473
Storey 8	0.01378	0.01404	0.0039	0.0055	0.0042	0.0039	3.15	0.0473
Storey 7	0.0143	0.01378	0.0057	0.0057	0.0042	0.0039	3.15	0.0473
Storey 6	0.0143	0.01326	0.0060	0.0052	0.0042	0.0039	3.15	0.0473
Storey 5	0.01404	0.01248	0.0057	0.0052	0.0042	0.0039	3.15	0.0473
Storey 4	0.013	0.01144	0.0057	0.0049	0.0042	0.0034	3.15	0.0473
Storey 3	0.01144	0.00962	0.0049	0.0042	0.0036	0.0029	3.15	0.0473
Storey 2	0.00832	0.0078	0.0036	0.0036	0.0026	0.0026	3.15	0.0473
Storey 1	0.0078	0.00598	0.0034	0.0029	0.0023	0.0021	4.5	0.0675

5.2.2.3.6 P-Δ effects

As described in section 5.1.2.3.6 for building A, the P-Δ effects in building B was checked according to the following equation,

$$\theta = d_{st} \sum_{j=1}^{n} W_j \bigg/ \left(h_{si}\mu \sum_{j=1}^{n} F_j \right)$$

Where,

d_{st}: The design storey drift – From table AB-8, as appropriately for particular soil type.

W_j: Seismic weight of the structure or component at level *j* in kilo Newton – From table AB-1.

h_{si}: Inter-storey height of level *i*, measured from centre-line to centre-line of the floors.

μ: Structural ductility factor - From table AS-6.

F_j: Horizontal dynamic force at the *j*th level, obtained from response spectrum analysis - From table AB-8as appropriately.

The calculation procedure related to inter-storey stability coefficient(θ) for three different ground conditions are listed in table AB-11, AB-12 and AB-13.

Table AB-11 : Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Very soft soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	8,150	0.0120	0.0161	906	826	4	2	0.013	0.02
Storey 13	18,582	0.0099	0.0127	1627	1429	3.15	2	0.018	0.026
Storey 12	28,869	0.0109	0.0135	2193	1841	3.15	2	0.023	0.034
Storey 11	39,278	0.0117	0.0135	2683	2151	3.15	2	0.027	0.039
Storey 10	49,789	0.0125	0.0140	3119	2411	3.15	2	0.032	0.046
Storey 9	60,300	0.0133	0.0138	3506	2639	3.15	2	0.036	0.05
Storey 8	70,811	0.0138	0.0140	3855	2856	3.15	2	0.04	0.055
Storey 7	81,362	0.0143	0.0138	4175	3078	3.15	2	0.044	0.058
Storey 6	91,944	0.0143	0.0133	4469	3311	3.15	2	0.047	0.058
Storey 5	102,526	0.0140	0.0125	4733	3541	3.15	2	0.048	0.057
Storey 4	112,726	0.0130	0.0114	4965	3761	3.15	2	0.047	0.054
Storey 3	123,020	0.0114	0.0096	5157	3963	3.15	2	0.043	0.047
Storey 2	133,314	0.0083	0.0078	5298	4125	3.15	2	0.033	0.04
Storey 1	145,392	0.0078	0.0060	5396	4246	4.5	2	0.023	0.023

Table AB-12 : Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Shallow soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	8,150	0.0057	0.0070	630	610	4	2	0.009	0.012
Storey 13	18,582	0.0044	0.0057	1008	965	3.15	2	0.013	0.017
Storey 12	28,869	0.0047	0.0057	1228	1127	3.15	2	0.017	0.023
Storey 11	39,278	0.0052	0.0055	1378	1189	3.15	2	0.024	0.029
Storey 10	49,789	0.0052	0.0057	1489	1214	3.15	2	0.028	0.037
Storey 9	60,300	0.0073	0.0057	1580	1235	3.15	2	0.044	0.044
Storey 8	70,811	0.0039	0.0055	1668	1274	3.15	2	0.026	0.048
Storey 7	81,362	0.0057	0.0057	1767	1359	3.15	2	0.042	0.054
Storey 6	91,944	0.0060	0.0052	1884	1500	3.15	2	0.046	0.051
Storey 5	102,526	0.0057	0.0052	2023	1676	3.15	2	0.046	0.05
Storey 4	112,726	0.0057	0.0049	2179	1874	3.15	2	0.047	0.047
Storey 3	123,020	0.0049	0.0042	2346	2088	3.15	2	0.041	0.039
Storey 2	133,314	0.0036	0.0036	2499	2283	3.15	2	0.031	0.034
Storey 1	145,392	0.0034	0.0029	2624	2441	4.5	2	0.021	0.019

Table AB-13 :Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Rock conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	8,150	0.0042	0.0049	468	450	4	2	0.009	0.011
Storey 13	18,582	0.0034	0.0042	733	700	3.15	2	0.014	0.018
Storey 12	28,869	0.0034	0.0042	879	806	3.15	2	0.018	0.024
Storey 11	39,278	0.0036	0.0039	979	843	3.15	2	0.023	0.029
Storey 10	49,789	0.0039	0.0042	1060	866	3.15	2	0.029	0.038
Storey 9	60,300	0.0042	0.0042	1130	890	3.15	2	0.035	0.045
Storey 8	70,811	0.0042	0.0039	1199	925	3.15	2	0.039	0.047
Storey 7	81,362	0.0042	0.0039	1269	986	3.15	2	0.042	0.051
Storey 6	91,944	0.0042	0.0039	1347	1079	3.15	2	0.045	0.053
Storey 5	102,526	0.0042	0.0039	1439	1194	3.15	2	0.047	0.053
Storey 4	112,726	0.0042	0.0034	1546	1328	3.15	2	0.048	0.046
Storey 3	123,020	0.0036	0.0029	1667	1484	3.15	2	0.043	0.038
Storey 2	133,314	0.0026	0.0026	1785	1635	3.15	2	0.031	0.034
Storey 1	145,392	0.0023	0.0021	1886	1761	4.5	2	0.02	0.019

5.3 BUILDING "C"

The selected building is a 10 storied reinforced concrete apartment building, which includes a ground floor and 9 floors above. The basic descriptions and calculations of this structure are described in appendix C.

5.3.1 Design seismic action

Classification of building

Since this is an apartment building having less than 15 storeys, the building has been categorized as Importance level 2 (*Table AS-2*)

Reference probability of exceedance

Annual probability of the design event for safety for earthquake condition for Importance level 2 =1/500 (*Table AS-1*)

Probability factor, k_p

For annual probability of exceedance = 1/500, k_p=1.0(*Table AS-4*)

Hazard factor, *Z*

The hazard factor, Z for different locations in Australia is given in table 3.2 of AS 1170.4-2007. However, for Sri Lankan conditions, it was considered to be 0.1 throughout the country.

Sub-soil class

For verysoft soil conditions, sub-soil class = E_e

For Shallow soil condition, sub-soil class = C_e

For rock condition, sub-soil class = B_e

Selection of earthquake design category

Importance level: 2

Structure height, h_n : 31.46m< 50m

$k_pZ = 1.0 \times 0.1 = 0.1$

Therefore, according to table AS-3, the building shall be designed for earthquake design categories based on sub-soil classes as follows.

Sub-soil class E_e : Earthquake Design Category III (EDCIII)

Sub-soil class C_e : Earthquake Design Category II (EDCII)

Sub-soil class B_e : Earthquake Design Category II (EDCII)

Horizontal design response spectrum $C_d(T)$

$C_d(T)$ = $C(T)S_p/\mu$ (Equation 6.2(4) of AS 1170.4:2007)

= $K_pZC_h(T)S_p/\mu$ (Equation 6.2(5) of AS 1170.4:2007)

For a structure consists of ordinary moment-resisting frames in combination with a limited ductile shear walls,

S_p/μ = 0.38 (*Table AS-6*)

$C_d(T)$ = 0.1 X 0.38 X $C_h(T)$

$C_d(T)$ = 0.038 $C_h(T)$

5.3.2 Method of analysis

To calculate earthquake forces, the code recommends to use either equivalent static analysis or dynamic analysis for EDCII structures and only dynamic analysis for EDCIII structures (Clause 5.4.2.2 and 5.5.2.2 of AS 1170.4-2007). The vertical earthquake actions are not required to be considered, except parts and components. Therefore, in this research, a modal response spectrum analysis was performed on a three dimensional structural model of the building. However, equivalent static analysis was also performed in order to obtain the horizontal force acting on each storey, which has been used to determine accidental torsional effects as described in section 6.6 of AS 1170.4-2007.

5.3.2.1 Structural Model

A three dimensional mathematical model has been used in this analysis since it can represents the special distribution of the mass and the stiffness of the structure adequately. The model was created to fulfill all the requirements specified in the code as described in section 5.1.2.1 in case of building A.

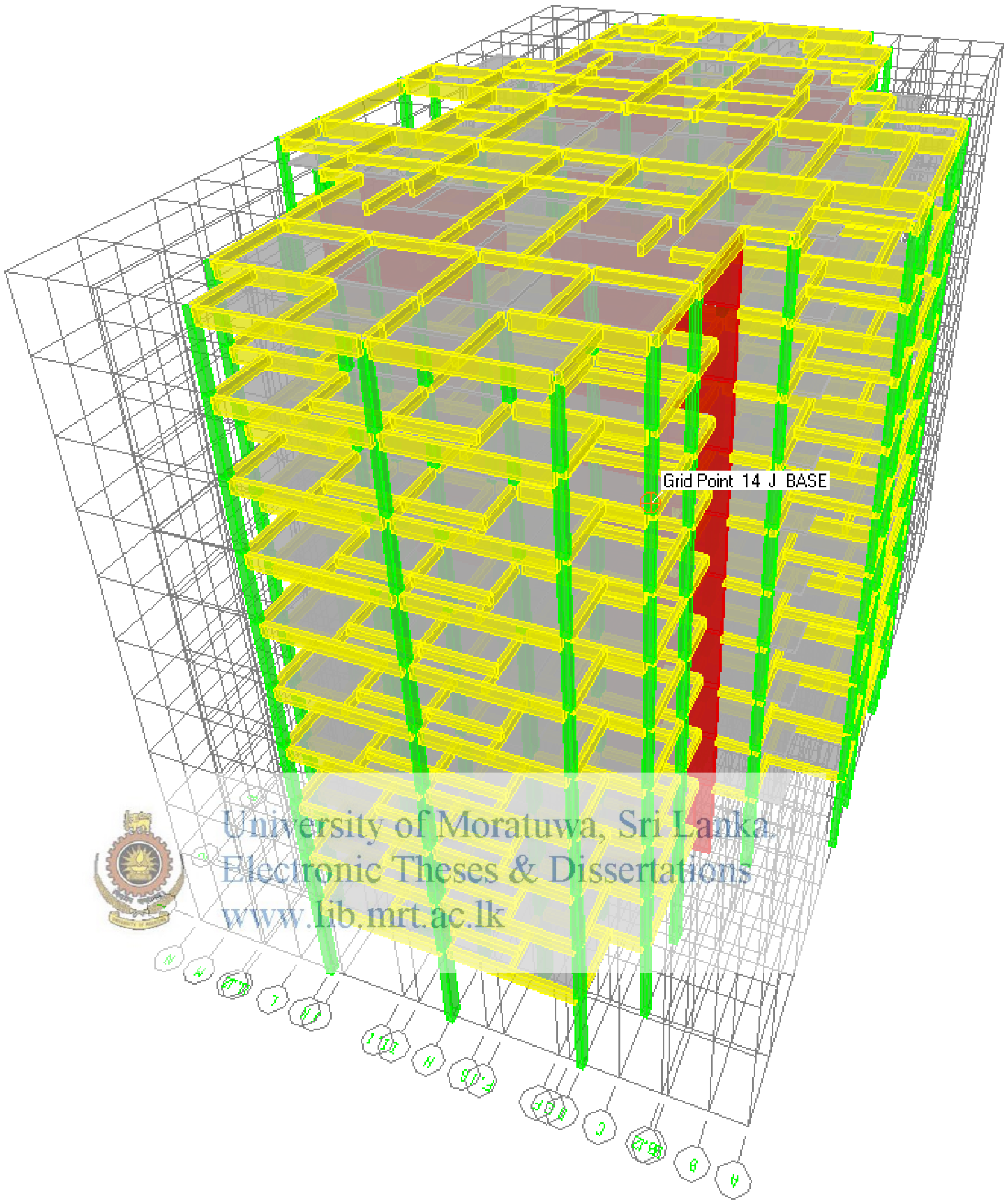

Figure AC-1: Three dimensional (spatial) model of building C

5.3.2.2 Equivalent static analysis

Equivalent static analysis can be carried out in three main steps as follows.

a). Estimating the self-weight and seismic masses of the building

b). Calculating the seismic base shear in relevant directions

c). Distribution of lateral forces and moments

5.3.2.2.1 Estimation of seismic weight of the building

As described in section 2.2.4.1 the seismic weight of the building can be found by following combination of dead load and the variable loads as,

$$W_i = \sum G_i + \sum \psi_c \cdot Q_{,i}$$

Table AC-1 : Total seismic weight of building C

Storey	ψ_c (Clause 6.2.2 of AS 1170.4-2007)	$G_{k,j}$ (kN)	$Q_{k,I}$ (kN)	Seismic weight (kN)	Total Seismic weight (kN)
Roof	0.3	5502	1460	5940	5940
Storey 9	0.3	7218	1526	7676	7676
Storey 8	0.3	7450	1526	7908	7908
Storey 7	0.3	7509	1526	7967	7967
Storey 4-6	0.3	7667	1526	8125	24375
Storey 3	0.3	7740	1526	8198	8198
Storey 2	0.3	7809	1526	8267	8267
Storey 1	0.3	8195	1526	8653	8653
Total seismic weight of the building					78,984

5.3.2.2.2 Calculating seismic base shear

The seismic base shear force for each horizontal direction is determined by the expression given in Clause 6.2.1 of AS 1170.4:2002.

$$V = C_d(T_1)W_t$$

$$C_d(T_1) = 0.0494C_h(T_1) \quad \text{(From section 5.3.1)}$$

$$V = 0.038C_h(T_1)W_t$$

T_1: The fundamental period of vibration of the building

From modal analysis - Refer Table A5

From eq.6.2(7) of AS 1170.4-2007 - When k_t= 0.05and

h_n= 31.46 m

T_1= 0.83 S

$C_h(T_1)$: The values of the spectral shape factors are obtained from table 6.4 of AS 1170.4:2007.

W_t : The seismic weight of the building - Refer table AC-1

The base shear force for each horizontal direction, based on T_1 calculated according to both of above methods are shown in Table AC-2 and AC-3.Base shear forces calculated using T_1, obtained from modal analysis were then checked weather they exceed 80% of the base shear values obtained with T_1 calculated using the above equation. Base shear forces of the structure, after the comparison are shown in Table AC-4.

Table AC-2 : Design seismic base shear of building C (T_1 from modal analysis)

Soil type	Fundamental period, T_1 (S) from modal analysis		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)	
	X	Y	X	Y					X	Y
Very soft soil	3.05	1.01	0.5	3.06	1	0.1	0.38	78,984	1,501	9,185
Shallow soil	3.05	1.01	0.21	1.24	1	0.1	0.38	78,984	631	3,722
Rock	3.05	1.01	0.15	0.88	1	0.1	0.38	78,984	451	2,642

Table AC-3 : Design seismic base shear of building C (T_1 from eq. 6.2(7) of AS 1170.4-2007)

Soil type	Fundamental period, T_1 (S) from eq.6.2(7) of AS 1170.4-2007		$C_h(T_1)$		K_p	Z	S_p/μ	W_t (kN)	V (kN)		80% of V (kN)	
	X	Y	X	Y					X	Y	X	Y
Very soft soil	0.83	0.83	3.61	3.61	1	0.1	0.38	78,984	10836	10836	8669	8669
Shallow soil	0.83	0.83	1.51	1.51	1	0.1	0.38	78,984	4533	4533	3626	3626
Rock	0.83	0.83	1.07	1.07	1	0.1	0.38	78,984	3212	3212	2570	2570

Table AC-4 : Design seismic base shear of building C

Soil type	Base Shear, V (kN)	
	X	Y
Very soft soil	8669	9,185
Shallow soil	3626	3,722
Rock	2570	2,642

5.3.2.2.3 Distribution of lateral forces

The seismic base shear (V) was then distributed at each storey level by using the following expression as shown in 2.2.4.3.1.3,

$F_i = k_{F,i}V$ (Refer AS 1170.4: 2007/eq 6.3(1))

$$= \frac{W_i {h_i}^k}{\sum_{j=1}^{n} W_j {h_j}^k} [K_p Z C_h(T_1) \frac{S_p}{\mu} /] W_t \text{ (Refer AS 1170.4: 2007/eq 6.2(2)}$$

The values for k in X direction (kx) and in Y direction (ky) were calculated according to Clause 6.3 of AS 1170.4-2002, as described in section 5.1.2.2.3, in case of building A.

The distribution of seismic base shear at each storey level is shown in Table AC-5

Table AC-5 : Distribution of seismic base shear - Building C

Storey	Height h_i (m)	k_x	k_y	h_i^{kx}	h_i^{ky}	Weight W_i (kN)	$W_i h_i^{kx}$	$W_i h_i^{ky}$	F_i(kN)					
									Very soft soil		Shallow soil		Rock	
									F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}
Roof	31.46	2.00	1.26	990	77	5,940	5,880,600	457,380	1,718	1,391	719	563	509	400
Storey 9	28.48	2.00	1.26	811	68	7,676	6,225,236	521,968	1,819	1,587	761	643	539	456
Storey 8	25.5	2.00	1.26	650	59	7,908	5,140,200	466,572	1,502	1,419	628	575	445	408
Storey 7	22.51	2.00	1.26	507	51	7,967	4,039,269	406,317	1,180	1,235	494	501	350	355
Storey 6	19.52	2.00	1.26	381	42	8,125	3,095,625	341,250	904	1,037	378	420	268	298
Storey 5	16.54	2.00	1.26	274	34	8,125	2,226,250	276,250	650	840	272	340	193	242
Storey 4	13.56	2.00	1.26	184	27	8,125	1,495,000	219,375	437	667	183	270	129	192
Storey 3	10.57	2.00	1.26	112	20	8,198	918,176	163,960	268	498	112	202	80	143
Storey 2	7.58	2.00	1.26	57	13	8,267	471,219	107,471	138	327	58	132	41	94
Storey 1	4.6	2.00	1.26	21	7	8,653	181,713	60,571	53	184	22	75	16	53
	Total						29,673,288	3,021,114	8,669	9,185	3,626	3,721	2,570	2,641

5.3.2.3 Modal response spectrum analysis

5.3.2.3.1. General rules

The general rules recommended for this type of analysis were followed in the case of the test building and are given as follows.

- Modal response spectrum analysis was performed independently for the ground excitation in two horizontal directions.
- For the combination of different modes, the “Complete Quadratic Combination (CQC) rule was used.
- The results of the modal analysis in both directions were combined by the SRSS rule.
- The load combinations were considered according to Clause 4.2.2 of AS 1170.0; 2002.
- The accidental torsional effect was considered by means of torsional moments about the vertical axis according to Clauses 7.4.4.1 and 6.6 of AS 1170.4-2007.

5.3.2.3.2 Periods and effective masses

In the modal response spectrum analysis, adequate modes of vibrations were taken in to account described in Clause 7.4.2 of AS1170.4-2007.

The basic modal properties are summarized in Table AC-6.

Table AC-6 : Periods and effective modal mass participation of building C (Modal response spectrum analysis

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	3.05	93.39	0.00
2	1.22	0.01	0.14
3	1.01	0.00	69.06
4	0.94	4.81	0.00
5	0.50	0.89	0.00
6	0.32	0.32	0.00
7	0.27	0.00	0.02
8	0.23	0.14	0.00
9	0.21	0.00	19.77
10	0.17	0.09	0.00
11	0.13	0.04	0.00
12	0.11	0.02	0.00
13	0.11	0.00	0.00
14	0.09	0.02	0.00
15	0.09	0.00	6.41
		99.73%	95.40%

5.3.2.3.3 Torsional effects

Similar in building A, as described in section 5.1.2.3.3, the accidental torsional effect has been considered by means of torsional moments ($M_{axi}$and M_{ayi}), applying about the vertical axis at each storey, i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey levels are listed in tables AC-7 for very soft soil, shallow soil and rock conditions respectively.

Table AC-7 : Torsional moments - Building C

Storey	L_{ix} (m)	L_{iy} (m)	e_{ix} (m)	e_{iy} (m)	Fi (kN)						Mi (kNm)					
					Very soft		Shallow		Rock		Very soft		Shallow		Rock	
					(m)	(m)	(m)	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	41.3	25.6	4.13	2.56	1,718	1,391	719	563	509	400	4398	5745	1841	2325	**1303**	**1652**
Storey 9	41.3	25.6	4.13	2.56	1,819	1,587	761	643	539	456	4657	6554	1948	2656	**1380**	**1883**
Storey 8	41.3	25.6	4.13	2.56	1,502	1,419	628	575	445	408	3845	5860	1608	2375	**1139**	**1685**
Storey 7	41.3	25.6	4.13	2.56	1,180	1,235	494	501	350	355	3021	5101	1265	2069	**896**	**1466**
Storey 6	41.3	25.6	4.13	2.56	904	1,037	378	420	268	298	2314	4283	968	1735	**686**	**1231**
Storey 5	41.3	25.6	4.13	2.56	650	840	272	340	193	242	1664	3469	696	1404	**494**	**999**
Storey 4	41.3	25.6	4.13	2.56	437	667	183	270	129	192	1119	2755	468	1115	**330**	**793**
Storey 3	41.3	25.6	4.13	2.56	268	498	112	202	80	143	686	2057	287	834	**205**	**591**
Storey 2	41.3	25.6	4.13	2.56	138	327	58	132	41	94	353	1351	148	545	**105**	**388**
Storey 1	41.3	25.6	4.13	2.56	53	184	22	75	16	53	136	760	56	310	**41**	**219**

5.3.2.3.4 Storey shear and displacements

In the case of test building, the storey shear forces and the displacement of the centre of mass of each floor level of the building were obtained by performing response spectrum analysis for the system. The design displacement values for three different soil conditions were calculated according to section 2.1.5.6.

Storey shear forces and displacement of the centre of mass of each floor level of the building are shown in table AC-8 and AC-9 respectively.

Table AC-8 : Storey shear forces of building C (Modal response spectrum analysis method)

Storey	Storey Shear (kN)					
	Very soft		Shallow		Rock	
	X	Y	X	Y	X	Y
Roof	377	1476	191	943	139	729
Storey 9	756	2942	341	1683	243	1282
Storey 8	1021	4081	433	2054	307	1530
Storey 7	1183	5012	493	2240	351	1624
Storey 6	1278	5797	534	2424	382	1723
Storey 5	1332	6460	563	2694	402	1913
Storey 4	1378	7011	589	3054	421	2198
Storey 3	1454	7457	616	3466	443	2537
Storey 2	1583	7779	655	3837	469	2847
Storey 1	1745	7954	720	4066	515	3039

Table AC-9: Design displacement (d_i) of the test building at each storey level (Modal response spectrum analysis method)

Storey	d_{ie}(m)						μ/Sp	d_i(m)					
	Very soft soil		Shallow soil		Rock			Very soft soil		Shallow soil		Rock	
	x	y	x	y	x	y		x	y	x	y	x	y
Roof	0.0555	0.0460	0.0229	0.0196	0.0164	0.0143	2.6	0.1443	0.1196	0.0595	0.0510	0.0426	0.0372
Storey 9	0.0545	0.0407	0.0225	0.0173	0.0161	0.0126	2.6	0.1417	0.1058	0.0585	0.0450	0.0419	0.0328
Storey 8	0.0520	0.0351	0.0214	0.0149	0.0154	0.0108	2.6	0.1352	0.0913	0.0556	0.0387	0.0400	0.0281
Storey 7	0.0489	0.0295	0.0201	0.0125	0.0144	0.0091	2.6	0.1271	0.0767	0.0523	0.0325	0.0374	0.0237
Storey 6	0.0459	0.0239	0.0189	0.0102	0.0135	0.0074	2.6	0.1193	0.0621	0.0491	0.0265	0.0351	0.0192
Storey 5	0.0426	0.0185	0.0175	0.0079	0.0125	0.0057	2.6	0.1108	0.0481	0.0455	0.0205	0.0325	0.0148
Storey 4	0.0387	0.0135	0.0159	0.0058	0.0114	0.0042	2.6	0.1006	0.0351	0.0413	0.0151	0.0296	0.0109
Storey 3	0.0343	0.0089	0.0141	0.0038	0.0101	0.0028	2.6	0.0892	0.0231	0.0367	0.0099	0.0263	0.0073
Storey 2	0.0294	0.0050	0.0121	0.0022	0.0086	0.0016	2.6	0.0764	0.0130	0.0315	0.0057	0.0224	0.0042
Storey 1	0.0224	0.0021	0.0092	0.0009	0.0066	0.0007	2.6	0.0582	0.0055	0.0239	0.0023	0.0172	0.0018

5.3.2.3.5 Storey drifts

The design drift(d_{st}) at each floor levels of the structure were evaluated similar way in building A, as described in section 5.1.2.3.5, considering the difference of the deflections (d_i) in centre of mass (CM) at the top and bottom of the storey, obtained by response spectrum analysis.

The inter-storey drift (d_{st}) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 1.5% of the storey height(h) according to clause 5.5.4 of AS 1170.4-2007.

All parameters for the verification of the damage limitation requirement for response spectrum analysis for different soil conditions are listed in Table AC-10.

Table AC-10: Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Building C

Storey	dst (m)						h (m)	1.5% h
	Very soft soil		Shallow soil		Rock			
	x	y	x	y	x	y		
Roof	0.0026	0.01378	0.0010	0.0060	0.0008	0.0044	2.985	0.0448
Storey 9	0.0065	0.01456	0.0029	0.0062	0.0018	0.0047	2.985	0.0448
Storey 8	0.00806	0.01456	0.0034	0.0062	0.0026	0.0044	2.985	0.0448
Storey 7	0.0078	0.01456	0.0031	0.0060	0.0023	0.0044	2.985	0.0448
Storey 6	0.00858	0.01404	0.0036	0.0060	0.0026	0.0044	2.985	0.0448
Storey 5	0.01014	0.013	0.0042	0.0055	0.0029	0.0039	2.985	0.0448
Storey 4	0.01144	0.01196	0.0047	0.0052	0.0034	0.0036	2.985	0.0448
Storey 3	0.01274	0.01014	0.0052	0.0042	0.0039	0.0031	2.985	0.0448
Storey 2	0.0182	0.00754	0.0075	0.0034	0.0052	0.0023	2.985	0.0448
Storey 1	0.05824	0.00546	0.0239	0.0023	0.0172	0.0018	4.6	0.069

5.3.2.3.6 P-Δ effects

As described in section 5.1.2.3.6 for building A, the P-Δ effects in building C was checked according to the following equation,

$$\theta = d_{st} \sum_{j=1}^{n} W_j \Big/ \left(h_{si} \mu \sum_{j=1}^{n} F_j \right)$$

Where,

d_{st}: The design storey drift – From table AC-8, as appropriately for particular soil type.

W_j: Seismic weight of the structure or component at level j in kilo Newton – From table AC-1.

h_{si}: Inter-storey height of level i, measured from centre-line to centre-line of the floors.

μ: Structural ductility factor - From table AS-6.

F_j: Horizontal dynamic force at the jth level, obtained from response spectrum analysis - From table AC-8 as appropriately.

The calculation procedure related to inter-storey stability coefficient(θ) for three different ground conditions are listed in table AC-11, AC-12 and AC-13.

Table AC-11 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Very soft soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	**5,940**	0.0026	0.0138	377	1476	2.985	2	0.007	0.009
Storey 9	**13,616**	0.0065	0.0146	756	2942	2.985	2	0.02	0.011
Storey 8	**21,524**	0.0081	0.0146	1021	4081	2.985	2	0.028	0.013
Storey 7	**29,491**	0.0078	0.0146	1183	5012	2.985	2	0.033	0.014
Storey 6	**37,616**	0.0086	0.0140	1278	5797	2.985	2	0.042	0.015
Storey 5	**45,741**	0.0101	0.0130	1332	6460	2.985	2	0.058	0.015
Storey 4	**53,866**	0.0114	0.0120	1378	7011	2.985	2	0.075	0.015
Storey 3	**62,064**	0.0127	0.0101	1454	7457	2.985	2	0.091	0.014
Storey 2	**70,331**	0.0182	0.0075	1583	7779	2.985	2	0.135	0.011
Storey 1	**78,984**	0.0582	0.0055	1745	7954	4.6	2	0.287	0.006

Table AC-12 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Shallow soil conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	5,940	0.0010	0.0060	191	943	2.985	2	0.005	0.006
Storey 9	13,616	0.0029	0.0062	341	1683	2.985	2	0.019	0.008
Storey 8	21,524	0.0034	0.0062	433	2054	2.985	2	0.028	0.011
Storey 7	29,491	0.0031	0.0060	493	2240	2.985	2	0.031	0.013
Storey 6	37,616	0.0036	0.0060	534	2424	2.985	2	0.043	0.016
Storey 5	45,741	0.0042	0.0055	563	2694	2.985	2	0.057	0.016
Storey 4	53,866	0.0047	0.0052	589	3054	2.985	2	0.072	0.015
Storey 3	62,064	0.0052	0.0042	616	3466	2.985	2	0.088	0.012
Storey 2	70,331	0.0075	0.0034	655	3837	2.985	2	0.136	0.01
Storey 1	78,984	0.0239	0.0023	720	4066	4.6	2	0.285	0.005

Table AC-13 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Rock conditions

Storey	Wj (kN)	d_{st} (m)		Storey shear, Fj (kN)		h	μ	θ	
		X	Y	X	Y	(m)		X	Y
Roof	5,940	0.0008	0.0044	139	729	2.985	2	0.006	0.006
Storey 9	13,616	0.0018	0.0047	243	1282	2.985	2	0.017	0.008
Storey 8	21,524	0.0026	0.0044	307	1530	2.985	2	0.031	0.01
Storey 7	29,491	0.0023	0.0044	351	1624	2.985	2	0.033	0.013
Storey 6	37,616	0.0026	0.0044	382	1723	2.985	2	0.043	0.016
Storey 5	45,741	0.0029	0.0039	402	1913	2.985	2	0.055	0.016
Storey 4	53,866	0.0034	0.0036	421	2198	2.985	2	0.072	0.015
Storey 3	62,064	0.0039	0.0031	443	2537	2.985	2	0.092	0.013
Storey 2	70,331	0.0052	0.0023	469	2847	2.985	2	0.131	0.01
Storey 1	78,984	0.0172	0.0018	515	3039	4.6	2	0.286	0.005

6 .0 ANALYSIS ACCORDING TO IS 1893(Part 1) : 2002

6.1 BUILDING "A"

The selected building is an eighteen storied reinforced concrete apartment building, which includes a Ground floor and seventeen above floors. The basic descriptions and calculations of this structure are described in appendix A.

6.1.1 Design seismic action

Zone factor, *Z*

The zone factor, *Z* for different zones in India is given in table 2 of IS1893 (Part 1) : 2002. However, the value of this factor has been considered as 0.1 for all areas in Sri Lanka, which also satisfy the requirement established for zone II.

Importance factor, *I*

This is an apartment building having 18 storeys. Therefore, according to note 2 of table 6 of IS 1893 (Part1) :2002, the important factor has been selected as 1.5.

Response reduction factor, *R*

Considering that the structure consists of ordinary shear wall and ordinary moment resisting frames, referring to table 7 of IS 1893 (Part1) :2002, the value of *R* was selected as 3.0.

Average response acceleration coefficient, *S*a/g

The value for *S*a/g for different soil conditions can be taken from figure 2 of IS 1893 (Part1) :2002, based on the natural period of vibration of the structure.

Design horizontal seismic coefficient (A_h)

$$A_h = \frac{ZIS_a}{2Rg}$$

Substituting the values for *Z*, *I* and *R*, as described above,

$A_h = 0.025\ Sa/g$

Structural Regularity

Clause 7.1 of *IS 1893-1:2002* defines the criteria to be satisfied in order a building to be considered as regular. Accordingly, a building shall be considered irregular, if any of the conditions given in table 4 and 5 *IS 1893-1:2002* are not satisfied. In case of the investigated building, as mentioned under the description of the project in appendix A, some of columns shift at fifth floor slab level. Therefore, the building was considered as irregular.

6.1.2 Method of analysis

Since the selected building is irregular and its height is more than 40m and located in an area similar to zone II, the design seismic forces were obtained by performing dynamic analysis, as described in section 7.8.1 of IS 1893 (Part 1) : 2002. Therefore a modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis has also been performed since the base shear force obtained by dynamic analysis has to be compared against that of calculated by static lateral force method. The shear forces, calculated by static lateral force method were also used to determine the accidental torsional moments, which were assigned in the model as specified in the code.

6.1.2.1 Structural Model

A three dimensional mathematical model was used in this analysis since it can represent the special distribution of the mass and the stiffness of the structure adequately.

In this study, the building was considered to have no significant structural effect from the masonry infill walls on its behavior when subjected to seismic load. The reinforced concrete frame wall system was considered as the only lateral load resisting system in the building and therefore, the presence of masonry infill walls were not considered in making the model. However, their weight was considered in the calculation of seismic weight of the building.

It is required that the model should fulfill all the requirements specified in the code. The basic characteristics of the model of the test building considering the requirements in the code are as follows.

- Column and beam elements are modeled as line elements whereas the floor slabs and concrete walls are modeled as shell elements.

- The elements were modeled with the actual sizes such that they adequately represent the distribution of stiffness and mass of the building.
- Even though it is not specifically discussed about the influence of cracked sections in IS 1893 (Part 1) : 2002, this influence was reflected in the model by multiplying the moment of inertia and shear area of the un-cracked sections by 0.5 in order to take the elastic flexural and shear properties one-half of those corresponding to un-cracked elements. Torsional stiffness of the cracked sections were set equal to 10% of the torsional stiffness of the un-cracked sections.
- Frames are connected by means of rigid diaphragms in horizontal plane at each floor level.
- The accidental torsional effects were considered by applying torsional moments about vertical axis as described in Clause 7.9 of IS 1893 (Part 1) : 2002.

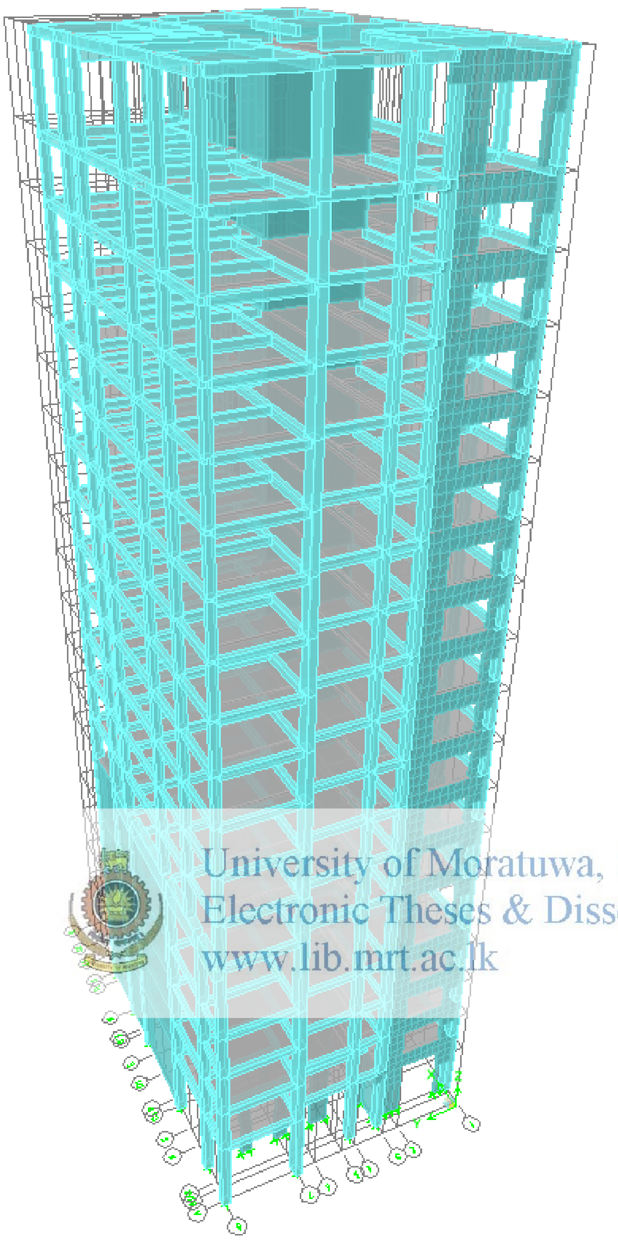

Figure IA-1: Three dimensional (spatial) model of building A

6.1.2.2. Lateral force method (Static analysis)

Analysis according to lateral force method can be carried out in three main steps as follows.

a). Estimating the self-weight and seismic weight of the building

b). Calculating the seismic base shear in relevant directions

c). Distribution of lateral forces at each floor level.

6.1.2.2.1 Seismic weight of the building

The seismic weight of the building was calculated considering both the dead load and the variable loads as described in section 2.3.4.1.

Table IA-1 : Seismic weight of building A

Storey	$G_{k,j}$ (kN)	$Q_{k,I}$ (t)	Percentage of $Q_{k,I}$ to be considered	$Q_{k,I}$ to be considered (kN)	Seismic weight (kN)	Total Seismic weight (kN)
Roof	4911	811	0%	0.00	4,911.00	4,911.00
Storey 17	6340	811	25%	202.75	6,542.75	6,542.75
Storey 7-16	5952	811	25%	202.75	6,154.75	61,547.50
Storey 6	6032	811	25%	202.75	6,234.75	6,234.75
Storey 5	7652	811	25%	202.75	7,854.75	7,854.75
Storey 4	6279	1227	25%	306.75	6,585.75	6,585.75
Storey 3-2	5620	1227	25%	306.75	5,926.75	11,853.50
Storey 1	6372	1227	25%	306.75	6,678.75	6,678.75
Total seismic weight of the building						112,209

6.1.2.2.2 Design seismic base shear

The total design seismic base shear (V_B) for each horizontal direction has been determined by the expression given in Clause 7.5.3 of IS 1893 (Part 1) : 2002 as,

$$V_B = A_h W$$

Where

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration.

W: Seismic weight of the building - Refer table IA-1.

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration, which was calculated in 6.1.1 as 0.025 Sa/g, where Sa/g can be found from figure IA-1, with respect to fundamental natural period of vibration (T_a) in the relevant direction

Fundamental period of vibration

The fundamental natural period of vibration (T_a) has been obtained by model analysis performed on the three dimensional computer model of the building.

The design base shear force acting in each horizontal direction is shown in table IA-2.

Table IA-2 :Design seismic base shear by static lateral force method - Building A

Soil type	Fundamental period, T_a (S)		Z	I	R	Sa/g		W	VB (kN)	
	X	Y				X	Y	(kN)	X	Y
Soft soil	1.32	1.64	0.1	1.5	3	1.28	1.03	112,209	3,591	2,889
Medium soil	1.32	1.64	0.1	1.5	3	1.04	0.83	112,209	2,917	2,328
Hard soil	1.32	1.64	0.1	1.5	3	0.77	0.62	112,209	2,160	1,739

6.1.2.2.3 Distribution of lateral forces

The design base shear (V_B) was then distributed along the height of the building as per the following expression (Refer IS 1893-1:2002/7.7.1);

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Where

Q_i: Design lateral force at floor i,

W_i: Seismic weight of the floor i - From table IA-1,

h_i: Height of floor i measured from base ,

n: Number of storeys in the building is the number of levels at which the masses are located

The distribution of design seismic base shear at each storey level is shown in Table IA-3

Table IA-3: Distribution of design seismic base shear at each storey level - Building A

Storey	W_i (kN)	h_i (m)	$W_i h_i^2$	Q_i (kN)					
				Soft soil		Medium soil		Hard soil	
				Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}
Roof	4,911.00	71.2	24,896,020	439	354	357	285	264	213
Storey 17	6,542.75	66	28,500,219	503	405	409	326	303	244
Storey 16	6,154.75	62.4	23,965,119	423	340	344	274	254	205
Storey 15	6,154.75	58.8	21,279,679	376	302	305	244	226	182
Storey 14	6,154.75	55.2	18,753,769	331	266	269	215	199	160
Storey 13	6,154.75	51.6	16,387,391	289	233	235	188	174	140
Storey 12	6,154.75	48	14,180,544	250	201	203	162	151	121
Storey 11	6,154.75	44.4	12,133,228	214	172	174	139	129	104
Storey 10	6,154.75	40.8	10,245,443	181	146	147	117	109	88
Storey 9	6,154.75	37.2	8,517,189	150	121	122	97	90	73
Storey 8	6,154.75	33.6	6,948,467	123	99	100	80	74	59
Storey 7	6,154.75	30	5,539,275	98	79	79	63	59	47
Storey 6	6,234.75	26.4	4,345,371	77	62	62	50	46	37
Storey 5	7,854.75	22.8	4,083,213	72	58	59	47	43	35
Storey 4	6,585.75	16.8	1,858,762	33	26	27	21	20	16
Storey 3	5,926.75	13.2	1,032,677	18	15	15	12	11	9
Storey 2	5,926.75	9.6	546,209	10	8	8	6	6	5
Storey 1	6,678.75	6	240,435	4	3	3	3	3	2
Total (?)			203,453,010	3,591	2,890	2,918	2,329	2,161	1,740

6.1.2.3 Modal response spectrum analysis

6.1.2.3.1. General rules

The general rules recommended for this type of analysis were followed in case of the test building and are given as follows.

- Modal response spectrum analysis has been performed independently for the ground excitation in two horizontal directions. The excitation in vertical direction was not consider since the structure does not have large span beams, pre-stress components or cantilever projections.
- The acceleration spectrum defined in Clause 6.4.2 of IS 1893-1:2002 was used for the test building.
- For the combination of different modes, the "Complete Quadratic Combination (CQC) rule was used
- The results of the modal analysis in both directions were combined by the SRSS rule.
- The accidental torsional effect was considered by means of torsional moments applying about the vertical axis.

6.1.2.3.2 Periods and effective masses

In the modal response spectrum analysis, adequate number of modes of vibration were taken in to account as the sum of the modal masses in each horizontal directions to exceeds 90% of the total mass of the structure as given in Clause 7.8.4.2 of IS 1893-1:2002.

The basic modal properties are summarized in Table IA-4.

Table IA-4 : Periods and effective modal mass participation by modal response spectrum analysis - Building A

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	1.64	15.25	48.57
2	1.32	42.46	16.93
3	0.71	0.12	0.10
4	0.36	4.77	14.43
5	0.31	15.11	6.41
6	0.23	1.11	0.18
7	0.16	2.61	1.07
8	0.14	6.19	0.71
9	0.13	0.19	3.42
10	0.11	0.28	0.10
11	0.09	3.33	0.20
12	0.08	0.05	3.18
	M_{eff}	91.47%	95.30%

6.1.2.3.3 Torsional effects

The accidental eccentricity was taken as 5% of the floor dimension perpendicular to the direction of the seismic action, L_{ix} and L_{iy} as described in clause 7.9.2 of IS 1893-1:2002.

The accidental torsional effect was considered by means of torsional moments ($M_{axi}$and M_{ayi}) applied about the vertical axis at each storey,i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey levels are listed in tables IA-5 for soft, medium and hard soil conditions respectively.

Table IA-5 : Torsional moments - Building A

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	28.99	18.88	1.45	0.94	439	354	357	285	264	213	413	513	336	413	**248**	**309**
Storey 17	28.99	18.88	1.45	0.94	503	405	409	326	303	244	473	587	384	473	**285**	**354**
Storey 16	28.99	18.88	1.45	0.94	423	340	344	274	254	205	398	493	323	397	**239**	**297**
Storey 15	28.99	18.88	1.45	0.94	376	302	305	244	226	182	353	438	287	354	**212**	**264**
Storey 14	28.99	18.88	1.45	0.94	331	266	269	215	199	160	311	386	253	312	**187**	**232**
Storey 13	28.99	18.88	1.45	0.94	289	233	235	188	174	140	272	338	221	273	**164**	**203**
Storey 12	28.99	18.88	1.45	0.94	250	201	203	162	151	121	235	291	191	235	**142**	**175**
Storey 11	28.99	18.88	1.45	0.94	214	172	174	139	129	104	201	249	164	202	**121**	**151**
Storey 10	28.99	18.88	1.45	0.94	181	146	147	117	109	88	170	212	138	170	**102**	**128**
Storey 9	28.99	18.88	1.45	0.94	150	121	122	97	90	73	141	175	115	141	**85**	**106**
Storey 8	28.99	18.88	1.45	0.94	123	99	100	80	74	59	116	144	94	116	**70**	**86**
Storey 7	28.99	18.88	1.45	0.94	98	79	79	63	59	47	92	115	74	91	**55**	**68**
Storey 6	28.99	18.88	1.45	0.94	77	62	62	50	46	37	72	90	58	73	**43**	**54**
Storey 5	28.99	18.88	1.45	0.94	72	58	59	47	43	35	68	84	55	68	**40**	**51**
Storey 4	28.99	18.88	1.45	0.94	33	26	27	21	20	16	31	38	25	30	**19**	**23**
Storey 3	28.99	18.88	1.45	0.94	18	15	15	12	11	9	17	22	14	17	**10**	**13**
Storey 2	28.99	18.88	1.45	0.94	10	8	8	6	6	5	9	12	8	9	**6**	**7**
Storey 1	28.99	18.88	1.45	0.94	4	3	3	3	3	2	4	4	3	4	**3**	**3**

6.1.2.3.4 Storey shear forces by modal response spectrum analysis method

Storey shear forces were obtained by performing modal response spectrum analysis for the test building for three different soil conditions and they are listed in table IA-6.

When the design base shear (V_B), obtained by response spectrum analysis is lesser than the base shear ($\overline{V_B}$), obtained by equivalent static method, then, as per section 7.6 of IS 1893 (Part 1) : 2002, the response quantities like storey shear forces and displacements were multiplied by $\overline{V_B}/V_B$. The summary of base shear forces obtained by static and dynamic analysis methods are listed in IA-7 and storey shear forces after modification are listed in table IA-8.

Table IA-6 : Storey shear forces by modal response spectrum analysis method - Building A

Storey	Storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	288	256	268	239	248	223
Storey 17	476	435	435	400	394	366
Storey 16	619	576	554	522	488	468
Storey 15	727	685	637	610	544	536
Storey 14	813	770	698	674	575	575
Storey 13	886	838	746	719	593	595
Storey 12	951	896	789	755	608	605
Storey 11	1013	947	834	787	629	611
Storey 10	1078	997	885	820	665	622
Storey 9	1147	1050	947	859	720	645
Storey 8	1217	1107	1015	908	788	685
Storey 7	1287	1171	1085	968	862	744
Storey 6	1355	1242	1155	1039	939	819
Storey 5	1465	1375	1273	1178	1070	972
Storey 4	1527	1451	1339	1259	1143	1061
Storey 3	1573	1512	1389	1325	1199	1134
Storey 2	1604	1556	1423	1372	1237	1187
Storey 1	1623	1584	1444	1403	1260	1221

Table IA-7: Summary of base shear forces - Building A

Direction	Base shear force (kN)								
	Soft soil			Medium soil			Hard soil		
	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$
X	3,591	1623	2.2124	2,917	1444	2.0204	2,160	1260	1.7143
Y	2,889	1584	1.8241	2,328	1403	1.6595	1,739	1221	1.4244

Table IA-8 : Modified storey shear forces by modal response spectrum analysis method - Building A

Storey	Modified storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	637	467	541	397	425	318
Storey 17	1053	793	879	664	675	521
Storey 16	1369	1051	1119	866	837	667
Storey 15	1608	1250	1287	1012	933	763
Storey 14	1799	1405	1410	1119	986	819
Storey 13	1960	1529	1507	1193	1017	848
Storey 12	2104	1634	1594	1253	1042	862
Storey 11	2241	1727	1685	1306	1078	870
Storey 10	2385	1819	1788	1361	1140	886
Storey 9	2538	1915	1913	1426	1234	919
Storey 8	2692	2019	2051	1507	1351	976
Storey 7	2847	2136	2192	1606	1478	1060
Storey 6	2998	2266	2334	1724	1610	1167
Storey 5	3241	2508	2572	1955	1834	1385
Storey 4	3378	2647	2705	2089	1959	1511
Storey 3	3480	2758	2806	2199	2055	1615
Storey 2	3549	2838	2875	2277	2121	1691
Storey 1	3591	2889	2917	2328	2160	1739

6.1.2.3.5 Storey displacement and drift

In case of test building, the displacement of the centre of mass (CM) of each floor level of the building was obtained by performing response spectrum analysis for the system. The drift(d_r) at each floor levels of the structure was evaluated considering the difference of the deflections (d) in centre of mass (CM) at the top and bottom of the storey.

As described in section 7.11.1of IS 1893 (Part 1) :2002, for the purpose of displacement requirements, it is not required to check the design seismic forces against lower bound limit, as defined in section 7.8.2 of IS 1893 (Part 1) :2002. Therefore the displacement values obtained from response spectrum analysis were used in calculating storey drifts without any modification. The inter-storey drift (d_r) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 0.004 times the storey height(h) according to clause 7.11.1of IS 1893 (Part 1) :2002.

The displacement values at each storey for soft, medium and hard soil conditions are listed in table IA-9 and all the parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in Table IA-10. The displacement values after modifications are also listed in table IA-11. The displacement values listed, in Table IA-9 were then adjusted by multiplying by 2R to obtain the displacement values at ultimate limit state at Maximum Considered Earth Quake (MCE) situation. The adjusted displacement values are listed in Table IA-12.

Table IA-9 : Storey displacement (d) by modal response spectrum analysis method - Building A

Storey	Storey displacement, d in (m)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	0.0301	0.0305	0.0258	0.0257	0.0208	0.0204
Storey 17	0.0269	0.0279	0.023	0.0236	0.0185	0.0188
Storey 16	0.0247	0.0261	0.0211	0.0221	0.0169	0.0176
Storey 15	0.0225	0.0243	0.0191	0.0206	0.0153	0.0165
Storey 14	0.0202	0.0225	0.0172	0.0191	0.0138	0.0153
Storey 13	0.018	0.0207	0.0153	0.0176	0.0122	0.0141
Storey 12	0.0158	0.0188	0.0134	0.016	0.0107	0.0129
Storey 11	0.0136	0.017	0.0116	0.0145	0.0092	0.0116
Storey 10	0.0116	0.0151	0.0098	0.0129	0.0078	0.0104
Storey 9	0.0095	0.0132	0.0081	0.0113	0.0064	0.0091
Storey 8	0.0076	0.0113	0.0065	0.0097	0.0051	0.0078
Storey 7	0.0059	0.0095	0.0049	0.0081	0.0039	0.0066
Storey 6	0.0043	0.0077	0.0036	0.0065	0.0028	0.0053
Storey 5	0.0031	0.0059	0.0026	0.005	0.002	0.004
Storey 4	0.0017	0.0036	0.0014	0.0031	0.0011	0.0025
Storey 3	0.0012	0.0024	0.001	0.0021	0.0008	0.0017
Storey 2	0.0007	0.0014	0.0006	0.0012	0.0005	0.001
Storey 1	0.0003	0.0006	0.0003	0.0006	0.0002	0.0005

Table IA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building A

Storey	Storey drift (dr), m						Storey height (h), m	0.004h
	Soft soil		Medium soil		Hard soil			
	x	y	x	y	x	y		
Roof	0.0032	0.0026	0.0028	0.0021	0.0023	0.0016	5.2	0.0208
Storey 17	0.0022	0.0018	0.0019	0.0015	0.0016	0.0012	3.6	0.0144
Storey 16	0.0022	0.0018	0.0020	0.0015	0.0016	0.0011	3.6	0.0144
Storey 15	0.0023	0.0018	0.0019	0.0015	0.0015	0.0012	3.6	0.0144
Storey 14	0.0022	0.0018	0.0019	0.0015	0.0016	0.0012	3.6	0.0144
Storey 13	0.0022	0.0019	0.0019	0.0016	0.0015	0.0012	3.6	0.0144
Storey 12	0.0022	0.0018	0.0018	0.0015	0.0015	0.0013	3.6	0.0144
Storey 11	0.002	0.0019	0.0018	0.0016	0.0014	0.0012	3.6	0.0144
Storey 10	0.0021	0.0019	0.0017	0.0016	0.0014	0.0013	3.6	0.0144
Storey 9	0.0019	0.0019	0.0016	0.0016	0.0013	0.0013	3.6	0.0144
Storey 8	0.0017	0.0018	0.0016	0.0016	0.0012	0.0012	3.6	0.0144
Storey 7	0.0016	0.0018	0.0013	0.0016	0.0011	0.0013	3.6	0.0144
Storey 6	0.0012	0.0018	0.0010	0.0015	0.0008	0.0013	3.6	0.0144
Storey 5	0.0014	0.0023	0.0012	0.0019	0.0009	0.0015	6	0.024
Storey 4	0.0005	0.0012	0.0004	0.0010	0.0003	0.0008	3.6	0.0144
Storey 3	0.0005	0.001	0.0004	0.0009	0.0003	0.0007	3.3	0.0132
Storey 2	0.0004	0.0008	0.0003	0.0006	0.0003	0.0005	3.6	0.0144
Storey 1	0.0003	0.0006	0.0003	0.0006	0.0002	0.0005	6	0.024

Table IA-11 : Modified storey displacements by modal response spectrum analysis method - Building A

Storey	Modified storey displacement, d in (m)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	0.0666	0.0556	0.0521	0.0426	0.0357	0.0291
Storey 17	0.0595	0.0509	0.0465	0.0392	0.0317	0.0268
Storey 16	0.0546	0.0476	0.0426	0.0367	0.029	0.0251
Storey 15	0.0498	0.0443	0.0386	0.0342	0.0262	0.0235
Storey 14	0.0447	0.041	0.0348	0.0317	0.0237	0.0218
Storey 13	0.0398	0.0378	0.0309	0.0292	0.0209	0.0201
Storey 12	0.035	0.0343	0.0271	0.0266	0.0183	0.0184
Storey 11	0.0301	0.031	0.0234	0.0241	0.0158	0.0165
Storey 10	0.0257	0.0275	0.0198	0.0214	0.0134	0.0148
Storey 9	0.021	0.0241	0.0164	0.0188	0.011	0.013
Storey 8	0.0168	0.0206	0.0131	0.0161	0.0087	0.0111
Storey 7	0.0131	0.0173	0.0099	0.0134	0.0067	0.0094
Storey 6	0.0095	0.014	0.0073	0.0108	0.0048	0.0075
Storey 5	0.0069	0.0108	0.0053	0.0083	0.0034	0.0057
Storey 4	0.0038	0.0066	0.0028	0.0051	0.0019	0.0036
Storey 3	0.0027	0.0044	0.002	0.0035	0.0014	0.0024
Storey 2	0.0015	0.0026	0.0012	0.002	0.0009	0.0014
Storey 1	0.0007	0.0011	0.0006	0.001	0.0003	0.0007

Table IA-12 : Adjusted storey displacements by modal response spectrum analysis method - Building A

Storey	Multiplier to obtain displacements at ULT at MCE situation (2R)	Displacement at ULT at MCE situation, d in (m)					
		Soft soil		Medium soil		Hard soil	
		X	Y	X	Y	X	Y
Roof	6	0.1806	0.183	0.1548	0.1542	0.1248	0.1224
Storey 17	6	0.1614	0.1674	0.138	0.1416	0.111	0.1128
Storey 16	6	0.1482	0.1566	0.1266	0.1326	0.1014	0.1056
Storey 15	6	0.135	0.1458	0.1146	0.1236	0.0918	0.099
Storey 14	6	0.1212	0.135	0.1032	0.1146	0.0828	0.0918
Storey 13	6	0.108	0.1242	0.0918	0.1056	0.0732	0.0846
Storey 12	6	0.0948	0.1128	0.0804	0.096	0.0642	0.0774
Storey 11	6	0.0816	0.102	0.0696	0.087	0.0552	0.0696
Storey 10	6	0.0696	0.0906	0.0588	0.0774	0.0468	0.0624
Storey 9	6	0.057	0.0792	0.0486	0.0678	0.0384	0.0546
Storey 8	6	0.0456	0.0678	0.039	0.0582	0.0306	0.0468
Storey 7	6	0.0354	0.057	0.0294	0.0486	0.0234	0.0396
Storey 6	6	0.0258	0.0462	0.0216	0.039	0.0168	0.0318
Storey 5	6	0.0186	0.0354	0.0156	0.03	0.012	0.024
Storey 4	6	0.0102	0.0216	0.0084	0.0186	0.0066	0.015
Storey 3	6	0.0072	0.0144	0.006	0.0126	0.0048	0.0102
Storey 2	6	0.0042	0.0084	0.0036	0.0072	0.003	0.006
Storey 1	6	0.0018	0.0036	0.0018	0.0036	0.0012	0.003

6.2 BUILDING "B"

The selected building is a fourteen storied reinforced concrete apartment building, which includes a Ground floor and thirteen above floors. The basic descriptions and calculations of this structure are described in appendix B.

6.2.1 Design seismic action

Zone factor, *Z*

The zone factor, *Z* for different zones in India is given in table 2 of IS1893 (Part 1) : 2002. However, the value of this factor has been considered as 0.1 for all areas in Sri Lanka, which also satisfy the requirement established for zone II.

Importance factor, *I*

This is an apartment building having 14 storeys. Therefore, according to note 2 of table 6 of IS 1893 (Part1) :2002, the important factor was selected as 1.5.

Response reduction factor, *R*

Considering that the structure consists of ordinary shear wall and ordinary moment resisting frames, referring to table 7 of IS 1893 (Part1) :2002, the value of *R* was selected as 3.0.

Average response acceleration coefficient, *S*a/g

The value for *S*a/g for different soil conditions can be taken from figure 2 of IS 1893 (Part1) :2002, based on the natural period of vibration of the structure.

Design horizontal seismic coefficient (A_h)

$$A_h = \frac{ZIS_a}{2Rg}$$

Substituting the values for *Z*, *I* and *R*, as described above,

$A_h = 0.025\ Sa/g$

Structural Regularity

Clause 7.1 of *IS 1893-1:2002* defines the criteria to be satisfied in order a building to be considered as regular. Accordingly, a building shall be considered irregular, if any of the conditions given in table 4 and 5 *IS 1893-1:2002* are not satisfied. In case of the investigated building, as mentioned under the description of the project in appendix B, some of columns shift at first floor slab level. Therefore, the building was considered as irregular.

6.2.2 Method of analysis

Since the selected building is irregular and its height is more than 40 m and located in an area similar to zone II, the design seismic forces were obtained by performing dynamic analysis, as described in section 7.8.1 of IS 1893 (Part 1) : 2002. Therefore a modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis has also been performed since the base shear force obtained by dynamic analysis has to be compared against that of calculated by static lateral force method. The shear forces, calculated by static lateral force method were also used to determine the accidental torsional moments, which were assigned in the model as specified in the code.

6.2.2.1 Structural Model

A three dimensional mathematical model was used in this analysis since it can represent the special distribution of the mass and the stiffness of the structure adequately.

In this study, the building was considered to have no significant structural effect from the masonry infill walls on its behavior when subjected to seismic load. The reinforced concrete frame wall system was considered as the only lateral load resisting system in the building and therefore, the presence of masonry infill walls were not considered in making the model. However, their weight was considered in the calculation of seismic weight of the building.

As described in section 6.1.2.1 in case of building A, the model for this building was also developed fulfilling all the requirements specified in the code.

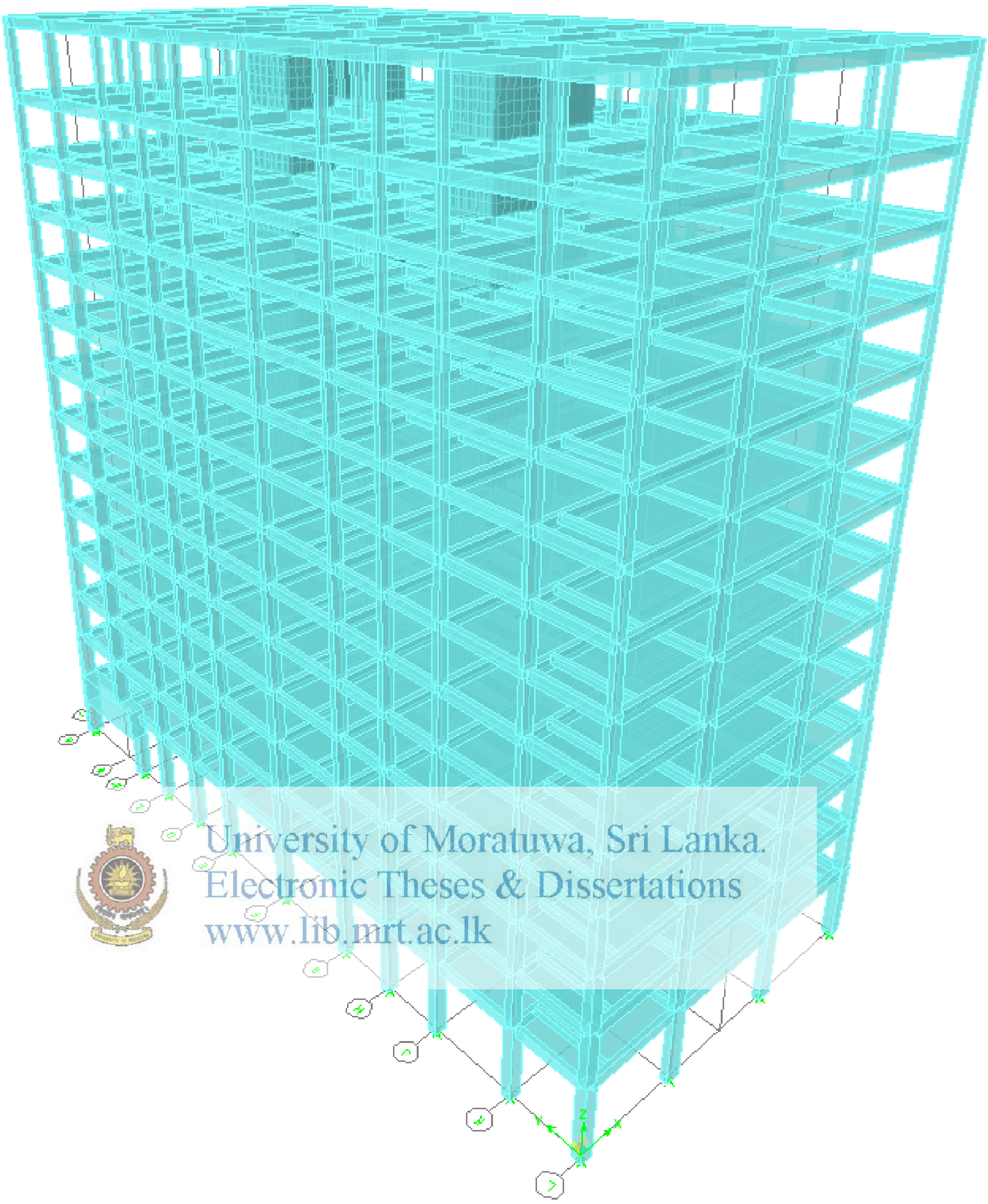

Figure IB-1 : Three dimensional (spatial) model of building B

6.2.2.2. Equivalent static analysis

As described in section 6.1.2.2, the analysis according to lateral force method can be carried out in three main steps as follows.

a) Estimating the self-weight and seismic weight of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces at each floor level.

6.2.2.2.1 Seismic weight of the building

The seismic weight of the building was calculated considering both the dead load and the variable loads as described in section 2.3.4.1.

Table IB-1 : Seismic weight of building B

Storey	$G_{k,j}$ (kN)	$Q_{k,I}$ (t)	Percentage of $Q_{k,I}$ to be considered	$Q_{k,I}$ to be considered (kN)	Seismic weight (kN)	Total Seismic weight (kN)
Roof	7602	1826	0%	0.00	7,602.00	7,602.00
Storey 13	9884	1826	25%	456.50	10,340.50	10,340.50
Storey 12	9739	1826	25%	456.50	10,195.50	10,195.50
Storey 11	9861	1826	25%	456.50	10,317.50	10,317.50
Storey 8-10	9963	1826	25%	456.50	10,419.50	31,258.50
Storey 7	10003	1826	25%	456.50	10,459.50	10,459.50
Storey 5-6	10034	1826	25%	456.50	10,490.50	20,981.00
Storey 4	10145	1826	25%	456.50	10,601.50	10,601.50
Storey 2-3	10239	1826	25%	456.50	10,695.50	21,391.00
Storey 1	12023	1826	25%	456.50	12,479.50	12,479.50
Total seismic weight of the building						145,627

6.2.2.2.2 Design seismic base shear

The total design seismic base shear (V_B) for each horizontal direction was determined by the expression given in Clause 7.5.3 of IS 1893 (Part 1) : 2002 as,

$$V_B = A_h W$$

Where

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration.

W: Seismic weight of the building - Refer table IB-1.

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration, which was calculated in 6.2.1 as 0.025 Sa/g, where Sa/g can be found from figure IB-1 with respect to fundamental natural period of vibration (T_a) in the relevant direction

Fundamental period of vibration

The fundamental natural period of vibration (T_a) has been obtained by model analysis performed on the three dimensional computer model of the building, The design base shear force acting in each horizontal direction is shown in table IB-2.

Table IB-2: Design seismic base shear by equivalent static method - Building B

Soil type	Fundamental period,Ta (S)		Z	I	R	Sa/g		W	VB (kN)	
	X	Y				X	Y	(kN)	X	Y
Soft soil	1.44	1.59	0.1	1.5	3	1.17	1.06	145,627	4,260	3,859
Medium soil	1.44	1.59	0.1	1.5	3	0.95	0.86	145,627	3,459	3,131
Hard soil	1.44	1.59	0.1	1.5	3	0.7	0.63	145,627	2,548	2,294

6.2.2.2.3 Distribution of lateral forces

The design base shear (V_B) was then distributed along the height of the building as per the following expression (Refer IS 1893-1:2002/7.7.1);

$$Q_i = V_B \frac{w_i}{\sum_{j=1}^{n} W_j h_j^2} h_i^2$$

Where

Q_i: Design lateral force at floor *i*,

W_i: Seismic weight of the floor *i* - From table IB-1,

h_i: Height of floor i measured from base ,

n: Number of storeys in the building is the number of levels at which the masses are located

The distribution of design seismic base shear at each storey level is shown in table IB-3

Table IB-3: Distribution of design seismic base shear at each storey level - Building B

Storey	W_i (kN)	h_i (m)	$W_i h_i^2$	Q_i (kN)					
				Soft soil		Medium soil		Hard soil	
				Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}
Roof	7,602.00	46.3	16,296,331	638	578	518	469	381	343
Storey 13	10,340.50	42.3	18,502,153	724	656	588	532	433	390
Storey 12	10,195.50	39.15	15,626,872	611	554	496	449	366	329
Storey 11	10,317.50	36	13,371,480	523	474	425	384	313	282
Storey 10	10,419.50	32.85	11,243,917	440	399	357	323	263	237
Storey 9	10,419.50	29.7	9,190,937	360	326	292	264	215	194
Storey 8	10,419.50	26.55	7,344,732	287	260	233	211	172	155
Storey 7	10,459.50	23.45	5,751,705	225	204	183	165	135	121
Storey 6	10,490.50	20.25	4,301,761	168	152	137	124	101	91
Storey 5	10,490.50	17.1	3,067,527	120	109	97	88	72	65
Storey 4	10,601.50	13.95	2,063,078	81	73	66	59	48	43
Storey 3	10,695.50	10.8	1,247,523	49	44	40	36	29	26
Storey 2	10,695.50	7.65	625,927	24	22	20	18	15	13
Storey 1	12,479.50	4.5	252,710	10	9	8	7	6	5
		Total	108,886,653	4,260.00	3,860.00	3,460.00	3,129.00	2,549.00	2,294.00

6.2.2.3 Modal response spectrum analysis

6.2.2.3.1 General rules

As described in section 6.1.2.3.1 in case of building A, the general rules recommended for this type of analysis were followed in case of the test building as well.

6.2.2.3.2 Periods and effective masses

In the modal response spectrum analysis, adequate number of modes of vibration are taken in to account as the sum of the modal masses in each horizontal directions exceeds 90% of the total mass of the structure as given in Clause 7.8.4.2 of IS 1893-1:2002.

The basic modal properties are summarized in table IB-4.

Table IB-4 : Periods and effective modal mass participation by modal response spectrum analysis - Building B

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	1.73	0.58	21.24
2	1.59	0.86	46.59
3	1.44	70.86	0.12
4	0.54	0.08	1.17
5	0.42	12.07	2.45
6	0.41	1.75	14.51
7	0.28	0.01	0.36
8	0.20	6.06	0.02
9	0.18	0.01	6.51
	M_{eff}	92.28%	92.97%

6.2.2.3.3 Torsional effects

As described in section 6.1.2.3.3 in case of building A, the accidental torsional effect was considered by means of torsional moments (M_{axi} and M_{ayi}) applied about the vertical axis at each storey,i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces (F_{ix} and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey levels are listed in tables IB-5 for soft, medium and hard soil conditions respectively.

Table IB-5 : Torsional moments - Building B

Storey	L_{ix}	L_{iy}	e_{ix}	e_{iy}	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
	(m)	(m)	(m)	(m)	F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	20.6	44.3	1.03	2.22	638	578	518	469	381	343	1416	595	1150	483	**846**	**353**
Storey 13	20.6	44.3	1.03	2.22	724	656	588	532	433	390	1607	676	1305	548	**961**	**402**
Storey 12	20.6	44.3	1.03	2.22	611	554	496	449	366	329	1356	571	1101	462	**813**	**339**
Storey 11	20.6	44.3	1.03	2.22	523	474	425	384	313	282	1161	488	944	396	**695**	**290**
Storey 10	20.6	44.3	1.03	2.22	440	399	357	323	263	237	977	411	793	333	**584**	**244**
Storey 9	20.6	44.3	1.03	2.22	360	326	292	264	215	194	799	336	648	272	**477**	**200**
Storey 8	20.6	44.3	1.03	2.22	287	260	233	211	172	155	637	268	517	217	**382**	**160**
Storey 7	20.6	44.3	1.03	2.22	225	204	183	165	135	121	500	210	406	170	**300**	**125**
Storey 6	20.6	44.3	1.03	2.22	168	152	137	124	101	91	373	157	304	128	**224**	**94**
Storey 5	20.6	44.3	1.03	2.22	120	109	97	88	72	65	266	112	215	91	**160**	**67**
Storey 4	20.6	44.3	1.03	2.22	81	73	66	59	48	43	180	75	147	61	**107**	**44**
Storey 3	20.6	44.3	1.03	2.22	49	44	40	36	29	26	109	45	89	37	**64**	**27**
Storey 2	20.6	44.3	1.03	2.22	24	22	20	18	15	13	53	23	44	19	**33**	**13**
Storey 1	20.6	44.3	1.03	2.22	10	9	8	7	6	5	22	9	18	7	**13**	**5**

6.2.2.3.4 Storey shear forces by modal response spectrum analysis method

Storey shear forces were obtained by performing modal response spectrum analysis for the test building for three different soil conditions and they are listed in table IB-6.

When the design base shear (V_B), obtained by response spectrum analysis is lesser than the base shear ($\overline{V}_B$), obtained by equivalent static method, then, as per section 7.6 of IS 1893 (Part 1) : 2002, the response quantities like storey shear forces and displacements were multiplied by $\overline{V}_B/V_B$. The summary of base shear forces obtained by static and dynamic analysis methods are listed in IB-7 and storey shear forces after modification are listed in table IB-8.

.

Table IB-6: Storey shear forces by modal response spectrum analysis method - Building B

Storey	Storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	353	342	328	323	298	300
Storey 13	635	592	577	547	510	497
Storey 12	841	753	747	680	641	600
Storey 11	1004	862	871	756	719	642
Storey 10	1143	946	970	805	773	654
Storey 9	1270	1024	1060	852	819	666
Storey 8	1388	1105	1145	909	867	695
Storey 7	1497	1190	1228	977	919	745
Storey 6	1601	1282	1313	1061	980	818
Storey 5	1701	1381	1402	1158	1057	915
Storey 4	1797	1484	1495	1265	1146	1028
Storey 3	1883	1580	1581	1367	1236	1138
Storey 2	1944	1651	1644	1444	1304	1222
Storey 1	1982	1699	1685	1496	1348	1279

Table IB-7 : Summary of base shear forces - Building B

Direction	Base shear force (kN)								
	Soft soil			Medium soil			Hard soil		
	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$
X	4,260	1982	2.1491	3,459	1685	2.0526	2,548	1348	1.8906
Y	3,859	1699	2.2714	3,131	1496	2.0929	2,294	1279	1.7933

Table IB-8 : Modified storey shear forces by modal response spectrum analysis method - Building B

Storey	Modified storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	759	777	673	676	563	538
Storey 13	1365	1345	1184	1145	964	891
Storey 12	1807	1710	1533	1423	1212	1076
Storey 11	2158	1958	1788	1582	1359	1151
Storey 10	2456	2149	1991	1685	1461	1173
Storey 9	2729	2326	2176	1783	1548	1194
Storey 8	2983	2510	2350	1902	1639	1246
Storey 7	3217	2703	2521	2045	1737	1336
Storey 6	3441	2912	2695	2221	1853	1467
Storey 5	3656	3137	2878	2424	1998	1641
Storey 4	3862	3371	3069	2648	2167	1844
Storey 3	4047	3589	3245	2861	2337	2041
Storey 2	4178	3750	3374	3022	2465	2191
Storey 1	4260	3859	3459	3131	2549	2294

6.2.2.3.5 Storey displacement and drift

In case of test building, the displacement of the centre of mass (CM) of each floor level of the building was obtained by performing response spectrum analysis for the system. The drift(d_r) at each floor levels of the structure was evaluated considering the difference of the deflections (d) in centre of mass (CM) at the top and bottom of the storey.

As described in section 7.11.1of IS 1893 (Part 1) :2002, for the purpose of displacement requirements, it is not required to check the design seismic forces against lower bound limit, as defined in section 7.8.2 of IS 1893 (Part 1) :2002. Therefore the displacement values obtained from response spectrum analysis were used in calculating storey drifts without any modification. The inter-storey drift (d_r) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 0.004 times the storey height(h) according to clause 7.11.1of IS 1893 (Part 1) :2002.

The displacement values at each storey for soft, medium and hard soil conditions are listed in table IB-9 and all the parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in Table IB-10. The displacement values after modifications are also listed in table IB-11.The displacement values, listed in Table IB-9 were then adjusted, multiplying by 2R to obtain the displacement values at ultimate limit state at Maximum Considered Earth Quake (MCE) situation. The adjusted displacement values are listed in Table IB-12.

Table IB-9 : Storey displacement (d) by modal response spectrum analysis method - Building B

Storey	Modified storey displacement, d in (m)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	0.0514	0.0579	0.0408	0.044	0.0287	0.0285
Storey 13	0.0475	0.0522	0.0376	0.0396	0.0265	0.0256
Storey 12	0.0443	0.0477	0.0351	0.036	0.0246	0.0235
Storey 11	0.0408	0.0432	0.0322	0.0326	0.0225	0.0212
Storey 10	0.0372	0.0384	0.0294	0.0291	0.0206	0.0188
Storey 9	0.0333	0.0336	0.0263	0.0255	0.0183	0.0165
Storey 8	0.0292	0.0291	0.0232	0.022	0.0161	0.0143
Storey 7	0.0249	0.0243	0.0197	0.0184	0.0138	0.0122
Storey 6	0.0206	0.0198	0.0164	0.0151	0.0115	0.0099
Storey 5	0.0163	0.0154	0.0129	0.0117	0.0091	0.0079
Storey 4	0.0122	0.0114	0.0096	0.0086	0.0068	0.0057
Storey 3	0.0082	0.0068	0.0066	0.0059	0.0047	0.0039
Storey 2	0.0047	0.0043	0.0039	0.0033	0.0026	0.0023
Storey 1	0.0021	0.002	0.0016	0.0015	0.0013	0.0011

Table IB-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building B

Storey	Storey drift (dr), m						Storey height (h), m	0.004h
	Soft soil		Medium soil		Hard soil			
	x	y	x	y	x	y		
Roof	0.0018	0.0025	0.0016	0.0021	0.0012	0.0016	4	0.016
Storey 13	0.0015	0.002	0.0012	0.0017	0.0010	0.0012	3.15	0.0126
Storey 12	0.0016	0.002	0.0014	0.0016	0.0011	0.0013	3.15	0.0126
Storey 11	0.0017	0.0021	0.0014	0.0017	0.0010	0.0013	3.15	0.0126
Storey 10	0.0018	0.0021	0.0015	0.0017	0.0012	0.0013	3.15	0.0126
Storey 9	0.0019	0.002	0.0015	0.0017	0.0012	0.0012	3.15	0.0126
Storey 8	0.002	0.0021	0.0017	0.0017	0.0012	0.0012	3.15	0.0126
Storey 7	0.002	0.002	0.0016	0.0016	0.0012	0.0013	3.15	0.0126
Storey 6	0.002	0.0019	0.0017	0.0016	0.0013	0.0011	3.15	0.0126
Storey 5	0.0019	0.0018	0.0016	0.0015	0.0012	0.0012	3.15	0.0126
Storey 4	0.0019	0.002	0.0015	0.0013	0.0011	0.0010	3.15	0.0126
Storey 3	0.0016	0.0011	0.0013	0.0012	0.0011	0.0009	3.15	0.0126
Storey 2	0.0012	0.001	0.0011	0.0009	0.0007	0.0007	3.15	0.0126
Storey 1	0.001	0.0009	0.0008	0.0007	0.0007	0.0006	4.5	0.018

Table IB-11 : Modified storey displacements by modal response spectrum analysis method - Building B

Storey	Modified storey displacement, d in (m)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	0.0514	0.0579	0.0408	0.044	0.0287	0.0285
Storey 13	0.0475	0.0522	0.0376	0.0396	0.0265	0.0256
Storey 12	0.0443	0.0477	0.0351	0.036	0.0246	0.0235
Storey 11	0.0408	0.0432	0.0322	0.0326	0.0225	0.0212
Storey 10	0.0372	0.0384	0.0294	0.0291	0.0206	0.0188
Storey 9	0.0333	0.0336	0.0263	0.0255	0.0183	0.0165
Storey 8	0.0292	0.0291	0.0232	0.022	0.0161	0.0143
Storey 7	0.0249	0.0243	0.0197	0.0184	0.0138	0.0122
Storey 6	0.0206	0.0198	0.0164	0.0151	0.0115	0.0099
Storey 5	0.0163	0.0154	0.0129	0.0117	0.0091	0.0079
Storey 4	0.0122	0.0114	0.0096	0.0086	0.0068	0.0057
Storey 3	0.0082	0.0068	0.0066	0.0059	0.0047	0.0039
Storey 2	0.0047	0.0043	0.0039	0.0033	0.0026	0.0023
Storey 1	0.0021	0.002	0.0016	0.0015	0.0013	0.0011

Table IB-12 : Adjusted storey displacements by modal response spectrum analysis method - Building B

Storey	Multiplier to obtain displacements at ULT at MCE situation (2R)	Displacement at ULT at MCE situation, d in (m)					
		Soft soil		Medium soil		Hard soil	
		X	Y	X	Y	X	Y
Roof	6	0.1434	0.153	0.1194	0.126	0.0912	0.0954
Storey 13	6	0.1326	0.138	0.1098	0.1134	0.084	0.0858
Storey 12	6	0.1236	0.126	0.1026	0.1032	0.078	0.0786
Storey 11	6	0.114	0.114	0.0942	0.0936	0.0714	0.0708
Storey 10	6	0.1038	0.1014	0.0858	0.0834	0.0654	0.063
Storey 9	6	0.093	0.0888	0.0768	0.0732	0.0582	0.0552
Storey 8	6	0.0816	0.0768	0.0678	0.063	0.051	0.048
Storey 7	6	0.0696	0.0642	0.0576	0.0528	0.0438	0.0408
Storey 6	6	0.0576	0.0522	0.048	0.0432	0.0366	0.033
Storey 5	6	0.0456	0.0408	0.0378	0.0336	0.0288	0.0264
Storey 4	6	0.0342	0.03	0.0282	0.0246	0.0216	0.0192
Storey 3	6	0.0228	0.018	0.0192	0.0168	0.015	0.0132
Storey 2	6	0.0132	0.0114	0.0114	0.0096	0.0084	0.0078
Storey 1	6	0.006	0.0054	0.0048	0.0042	0.0042	0.0036

6.3 BUILDING "C"

The selected building is a 10 storied reinforced concrete apartment building, which includes a ground floor and 9 floors above. The basic descriptions and calculations of this structure are described in appendix C.

6.3.1 Design seismic action

Zone factor, *Z*

The zone factor, *Z* for different zones in India is given in table 2 of IS1893 (Part 1) : 2002. However, the value of this factor has been considered as 0.1 for all areas in Sri Lanka, which also satisfy the requirement established for zone II.

Importance factor, *I*

This is an apartment building having 10 storeys. Therefore, according to note 2 of table 6 of IS 1893 (Part1) :2002, the important factor was selected as 1.5.

Response reduction factor, *R*

Considering that the structure consists of ordinary shear wall and ordinary moment resisting frames, referring to table 7 of IS 1893 (Part1) :2002, the value of *R* was selected as 3.0.

Average response acceleration coefficient, *S*a/g

The value for *S*a/g for different soil conditions can be taken from figure 2 of IS 1893 (Part1) :2002, based on the natural period of vibration of the structure.

Design horizontal seismic coefficient (A_h)

$$A_h = \frac{ZIS_a}{2Rg}$$

Substituting the values for *Z*, *I* and *R*, as described above,

$A_h = 0.025\ Sa/g$

6.3.2 Method of analysis

The height of the selected building is nearly 40m. It is located in an area similar to zone II. The design seismic forces were obtained by performing dynamic analysis. A modal response spectrum analysis has been performed on a three dimensional structural model of the building. However, a static lateral force method of analysis has also been performed since the base shear force obtained by dynamic analysis has to be compared against that of calculated by static lateral force method. The shear forces, calculated by static lateral force method were also used to determine the accidental torsional moments, which were assigned in the model as specified in the code.

6.3.2.1Structural Model

A three dimensional mathematical model was used in this analysis since it can represent the special distribution of the mass and the stiffness of the structure adequately.

In this study, the building was considered to have no significant structural effect from the masonry infill walls on its behavior when subjected to seismic load. The reinforced concrete frame wall system was considered as the only lateral load resisting system in the building and therefore, the presence of masonry infill walls were not considered in making the model. However, their weight was considered in the calculation of seismic weight of the building.

As described in section 6.1.2.1 in case of building A, the model for this building was also developed fulfilling all the requirements specified in the code.

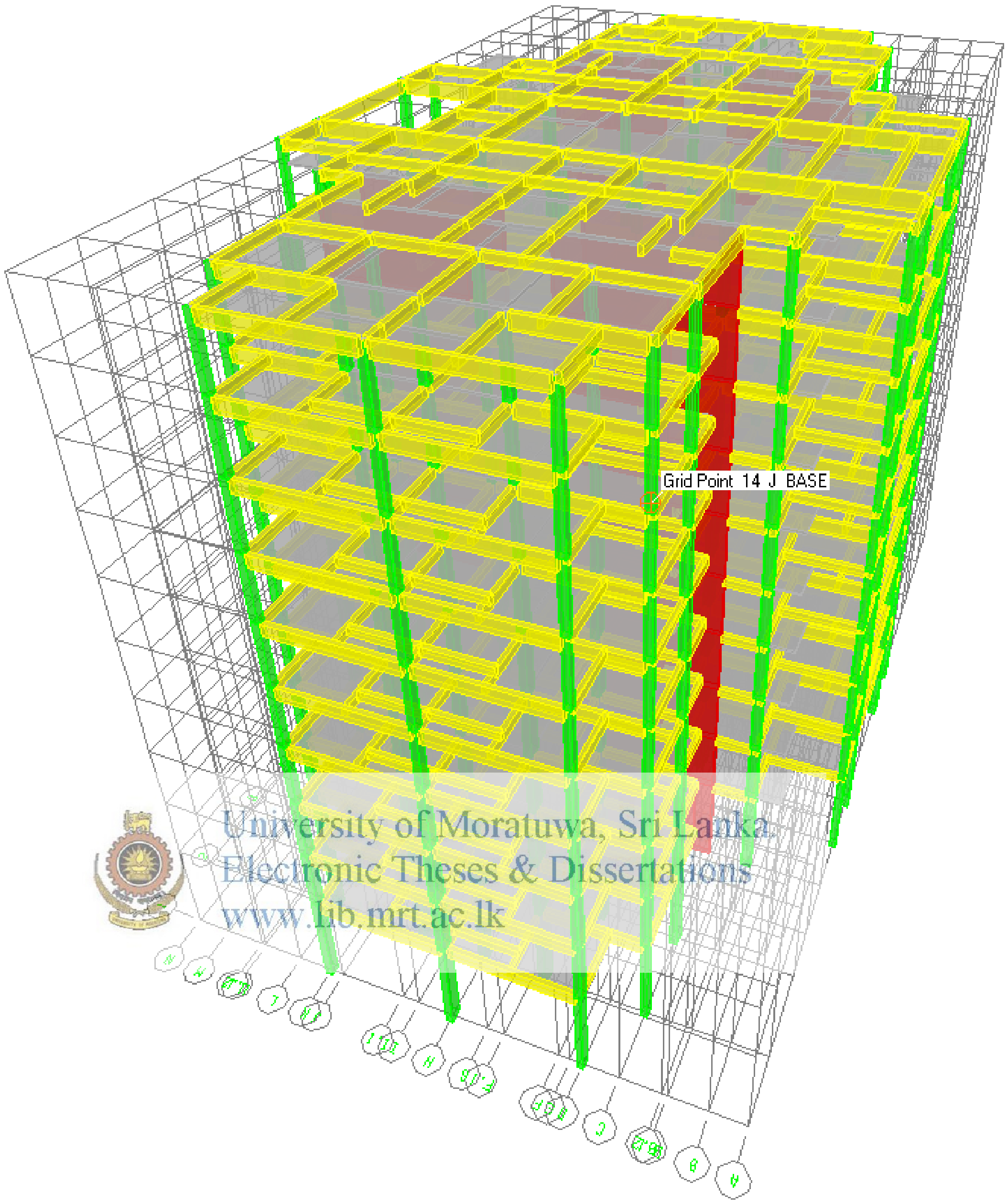

Figure IC-1: Three dimensional (spatial) model of building C

6.3.2.2. Equivalent static analysis

As described in section 6.1.2.2, the analysis according to lateral force method can be carried out in three main steps as follows.

a) Estimating the self-weight and seismic weight of the building
b) Calculating the seismic base shear in relevant directions
c) Distribution of lateral forces at each floor level.

6.3.2.2.1 Seismic weight of the building

The seismic weight of the building was calculated considering both the dead load and the variable loads as described in section 2.3.4.1.

Table IC-1 : Seismic weight of building C

Storey	$G_{k,j}$ (kN)	$Q_{k,I}$ (t)	Percentage of $Q_{k,I}$ to be considered	$Q_{k,I}$ to be considered (kN)	Seismic weight (kN)	Total Seismic weight (kN)
Roof	5502	1460	0%	0.00	5,502.00	5,502.00
Storey 9	7218	1526	25%	381.50	7,599.50	7,599.50
Storey 8	7450	1526	25%	381.50	7,831.50	7,831.50
Storey 7	7509	1526	25%	381.50	7,890.50	7,890.50
Storey 4-6	7667	1526	25%	381.50	8,048.50	24,145.50
Storey 3	7740	1526	25%	381.50	8,121.50	8,121.50
Storey 2	7809	1526	25%	381.50	8,190.50	8,190.50
Storey 1	8195	1526	25%	381.50	8,576.50	8,576.50
Total seismic weight of the building						77,858

6.3.2.2.2 Design seismic base shear

Similar to building A, as described in section 6.1.2.2, the total design seismic base shear (V_B) for each horizontal direction was determined by the expression given in Clause 7.5.3 of IS 1893 (Part 1): 2002 as,

$$V_B = A_h W$$

Where

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration.

W: Seismic weight of the building - Refer table IC-1.

A_h: Design horizontal acceleration spectrum value using the fundamental natural period T_a in the considered direction of vibration, which was calculated in 6.3.1 as 0.025 Sa/g, where Sa/g can be found from figure IC-1 with respect to fundamental natural period of vibration (T_a) in the relevant direction

Fundamental period of vibration

The fundamental natural period of vibration (T_a) has been obtained by model analysis performed on the three dimensional computer model of the building.

The design base shear force acting in each horizontal direction is shown in table IC-2.

Table IC-2 : Design seismic base shear by equivalent static method - Building C

Soil type	Fundamental period,Ta (S)		Z	I	R	Sa/g		W	VB (kN)	
	X	Y				X	Y	(kN)	X	Y
Soft soil	3.05	1.01	0.1	1.5	3	0.55	1.66	77,858	1,071	3,231
Medium soil	3.05	1.01	0.1	1.5	3	0.45	1.35	77,858	876	2,628
Hard soil	3.05	1.01	0.1	1.5	3	0.34	0.99	77,858	662	1,927

6.3.2.2.3 Distribution of lateral forces

The design base shear (V_B) was then distributed along the height of the building as per the following expression (Refer IS 1893-1:2002/7.7.1);

$$Q_i = V_B \frac{w_i h_i^2}{\sum_{j=1}^{n} w_j h_j^2}$$

Where

Q_i: Design lateral force at floor i,

W_i: Seismic weight of the floor i - From table IC-1,

h_i: Height of floor i measured from base ,

n: Number of storeys in the building is the number of levels at which the masses are located

The distribution of design seismic base shear at each storey level is shown in table IC-3

Table IC-3 : Distribution of design seismic base shear at each storey level - Building C

Storey	W_i (kN)	h_i (m)	$W_i h_i^2$	Q_i (kN)					
				Soft soil		Medium soil		Hard soil	
				Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}	Q_{ix}	Q_{iy}
Roof	5,502.00	31.46	5,445,503	201	607	164	493	124	362
Storey 9	7,599.50	28.48	6,164,033	227	687	186	558	141	409
Storey 8	7,831.50	25.5	5,092,433	188	567	154	461	116	338
Storey 7	7,890.50	22.51	3,998,117	148	445	121	362	91	266
Storey 6	8,048.50	19.52	3,066,723	113	342	93	278	70	204
Storey 5	8,048.50	16.54	2,201,841	81	245	66	199	50	146
Storey 4	8,048.50	13.56	1,479,907	55	165	45	134	34	98
Storey 3	8,121.50	10.57	907,374	33	101	27	82	21	60
Storey 2	8,190.50	7.58	470,597	17	52	14	43	11	31
Storey 1	8,576.50	4.6	181,479	7	20	5	16	4	12
		Total	29,008,007	1,070.00	3,231.00	875.00	2,626.00	662.00	1,926.00

6.3.2.3 Modal response spectrum analysis

6.3.2.3.1. General rules

As described in section 6.1.2.3.1 in case of building A, the general rules recommended for this type of analysis were followed in case of the test building as well.

6.3.2.3.2 Periods and effective masses

In the modal response spectrum analysis, adequate number of modes of vibration are taken in to account as the sum of the modal masses in each horizontal directions exceeds 90% of the total mass of the structure as given in Clause 7.8.4.2 of IS 1893-1:2002.

The basic modal properties are summarized in table IC-4.

Table IC-4 : Periods and effective modal mass participation by modal response spectrum analysis - Building C

Mode	T (s)	$M_{eff,UX}$ (%)	$M_{eff,UY}$ (%)
1	3.05	93.39	0.00
2	1.22	0.01	0.14
3	1.01	0.00	69.06
4	0.94	4.81	0.00
5	0.50	0.89	0.00
6	0.32	0.32	0.00
7	0.27	0.00	0.02
8	0.23	0.14	0.00
9	0.21	0.00	19.77
10	0.17	0.09	0.00
11	0.13	0.04	0.00
12	0.11	0.02	0.00
13	0.11	0.00	0.00
14	0.09	0.02	0.00
15	0.09	0.00	6.41
	M_{eff}	99.73%	95.40%

6.3.2.3.3 Torsional effects

As described in section 6.1.2.3.3 in case of building A, the accidental torsional effect was considered by means of torsional moments ($M_{axi}$and M_{ayi}) applied about the vertical axis at each storey,i. The envelop of the effects resulting from the four sets of torsional moments ($\pm M_{ix}$ and $\pm M_{iy}$) was then added to the combined (SRSS) results of the seismic actions in both horizontal directions.

The horizontal forces ($F_{ix}$and F_{iy}) for three soil conditions were obtained from the lateral force method of analysis. The calculation of torsional moments at each storey levels are listed in tables IC-5 for soft, medium and hard soil conditions respectively.

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Table IC-5 : Torsional moments - Building C

Storey	L_{ix} (m)	L_{iy} (m)	e_{ix} (m)	e_{iy} (m)	Fi(kN)						Mi(kNm)					
					Soft		Medium		Hard		Soft		Medium		Hard	
					F_{ix}	F_{iy}	F_{ix}	F_{iy}	F_{ix}	F_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}	M_{ix}	M_{iy}
Roof	41.3	25.6	2.07	1.28	201	607	164	493	124	362	257	1256	210	1021	**159**	**749**
Storey 9	41.3	25.6	2.07	1.28	227	687	186	558	141	409	291	1422	238	1155	**180**	**847**
Storey 8	41.3	25.6	2.07	1.28	188	567	154	461	116	338	241	1174	197	954	**148**	**700**
Storey 7	41.3	25.6	2.07	1.28	148	445	121	362	91	266	189	921	155	749	**116**	**551**
Storey 6	41.3	25.6	2.07	1.28	113	342	93	278	70	204	145	708	119	575	**90**	**422**
Storey 5	41.3	25.6	2.07	1.28	81	245	66	199	50	146	104	507	84	412	**64**	**302**
Storey 4	41.3	25.6	2.07	1.28	55	165	45	134	34	98	70	342	58	277	**44**	**203**
Storey 3	41.3	25.6	2.07	1.28	33	101	27	82	21	60	42	209	35	170	**27**	**124**
Storey 2	41.3	25.6	2.07	1.28	17	52	14	43	11	31	22	108	18	89	**14**	**64**
Storey 1	41.3	25.6	2.07	1.28	7	20	5	16	4	12	9	41	6	33	**5**	**25**

6.3.2.3.4 Storey shear forces by modal response spectrum analysis method

Storey shear forces were obtained by performing modal response spectrum analysis for the test building for three different soil conditions and they are listed in table IC-6.

When the design base shear (V_B), obtained by response spectrum analysis is lesser than the base shear ($\overline{V}_B$), obtained by equivalent static method, then, as per section 7.6 of IS 1893 (Part 1) : 2002, the response quantities like storey shear forces and displacements were multiplied by $\overline{V}_B/V_B$. The summary of base shear forces obtained by static and dynamic analysis methods are listed in IC-7 and storey shear forces after modification are listed in table IC-8.

Table IC-6 : Storey shear forces by modal response spectrum analysis method - Building C

Storey	Storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	178	568	152	507	118	444
Storey 9	368	1105	301	960	232	808
Storey 8	524	1497	431	1267	321	1014
Storey 7	654	1807	535	1495	397	1143
Storey 6	769	2072	630	1696	468	1262
Storey 5	871	2309	716	1888	532	1404
Storey 4	965	2519	794	2075	590	1570
Storey 3	1054	2703	865	2252	642	1748
Storey 2	1141	2845	934	2398	692	1905
Storey 1	1220	2926	1000	2484	741	2001

Table IC-7 : Summary of base shear forces - Building C

Direction	Base shear force (kN)								
	Soft soil			Medium soil			Hard soil		
	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$	Static ($\overline{V}_B$)	Dynamic (V_B)	$\overline{V}_B/V_B$
X	1,071	1220	0.8775	876	1000	0.8759	662	741	0.8931
Y	3,231	2926	1.1043	2,628	2484	1.0578	1,927	2001	0.963

Table IC-8 : Modified storey shear forces by modal response spectrum analysis method - Building C

Storey	Modified storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	178	627	152	536	118	444
Storey 9	368	1220	301	1015	232	808
Storey 8	524	1653	431	1340	321	1014
Storey 7	654	1995	535	1581	397	1143
Storey 6	769	2288	630	1794	468	1262
Storey 5	871	2550	716	1997	532	1404
Storey 4	965	2782	794	2195	590	1570
Storey 3	1054	2985	865	2382	642	1748
Storey 2	1141	3142	934	2537	692	1905
Storey 1	1220	3231	1000	2628	741	2001

6.3.2.3.5 Storey displacement and drift

In case of test building, the displacement of the centre of mass (CM) of each floor level of the building was obtained by performing response spectrum analysis for the system. The drift(d_r) at each floor levels of the structure was evaluated considering the difference of the deflections (d) in centre of mass (CM) at the top and bottom of the storey.

As described in section 7.11.1of IS 1893 (Part 1) :2002, for the purpose of displacement requirements, it is not required to check the design seismic forces against lower bound limit, as defined in section 7.8.2 of IS 1893 (Part 1) :2002. Therefore the displacement values obtained from response spectrum analysis were used in calculating storey drifts without any modification. The inter-storey drift (d_r) at each floor levels were then checked against the maximum allowable value for damage limitation requirement, given as 0.004 times the storey height(h) according to clause 7.11.1of IS 1893 (Part 1) :2002.

The displacement values at each storey for soft, medium and hard soil conditions are listed in table IC-9 and all the parameters for the verification of the damage limitation requirement for response spectrum analysis are listed in Table IC-10. The displacement values after modifications are also listed in table IC-11.The displacement values, listed in Table IC-9 were then adjusted, multiplying by 2*R* to obtain the displacement values at ultimate limit state at Maximum Considered Earth Quake (MCE) situation. The adjusted displacement values are listed in Table IC-12.

Table IC-9 : Storey displacement (d) by modal response spectrum analysis method - Building C

Storey	Storey displacement, d in (m)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	0.04	0.0174	0.0327	0.0144	0.0243	0.011
Storey 9	0.0392	0.0153	0.0321	0.0127	0.0238	0.0097
Storey 8	0.0377	0.0132	0.0309	0.011	0.0229	0.0084
Storey 7	0.0356	0.0111	0.0292	0.0092	0.0216	0.007
Storey 6	0.0335	0.009	0.0274	0.0074	0.0203	0.0057
Storey 5	0.0309	0.0069	0.0253	0.0058	0.0188	0.0044
Storey 4	0.028	0.005	0.0229	0.0042	0.017	0.0032
Storey 3	0.0246	0.0033	0.0201	0.0028	0.0149	0.0021
Storey 2	0.0209	0.0019	0.0171	0.0016	0.0127	0.0012
Storey 1	0.0159	0.0008	0.013	0.0006	0.0096	0.0005

Table IC-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building C

Storey	Storey drift (dr), m						Storey height (h), m	0.004h
	Soft soil		Medium soil		Hard soil			
	x	y	x	y	x	y		
Roof	0.0008	0.0021	0.0006	0.0017	0.0005	0.0013	2.985	0.0119
Storey 9	0.0015	0.0021	0.0012	0.0017	0.0009	0.0013	2.985	0.0119
Storey 8	0.0021	0.0021	0.0017	0.0018	0.0013	0.0014	2.985	0.0119
Storey 7	0.0021	0.0021	0.0018	0.0018	0.0013	0.0013	2.985	0.0119
Storey 6	0.0026	0.0021	0.0021	0.0016	0.0015	0.0013	2.985	0.0119
Storey 5	0.0029	0.0019	0.0024	0.0016	0.0018	0.0012	2.985	0.0119
Storey 4	0.0034	0.0017	0.0028	0.0014	0.0021	0.0011	2.985	0.0119
Storey 3	0.0037	0.0014	0.0030	0.0012	0.0022	0.0009	2.985	0.0119
Storey 2	0.005	0.0011	0.0041	0.0010	0.0031	0.0007	2.985	0.0119
Storey 1	0.0159	0.0008	0.0130	0.0006	0.0096	0.0005	4.6	0.0184

Table IC-11 : Modified storey displacements by modal response spectrum analysis method - Building C

Storey	Modified storey shear force (kN)					
	Soft soil		Medium soil		Hard soil	
	X	Y	X	Y	X	Y
Roof	178	627	152	536	118	444
Storey 9	368	1220	301	1015	232	808
Storey 8	524	1653	431	1340	321	1014
Storey 7	654	1995	535	1581	397	1143
Storey 6	769	2288	630	1794	468	1262
Storey 5	871	2550	716	1997	532	1404
Storey 4	965	2782	794	2195	590	1570
Storey 3	1054	2985	865	2382	642	1748
Storey 2	1141	3142	934	2537	692	1905
Storey 1	1220	3231	1000	2628	741	2001

Table IC-12 : Adjusted storey displacements by modal response spectrum analysis method - Building C

Storey	Multiplier to obtain displacements at ULT at MCE situation (2*R*)	Displacement at ULT at MCE situation, d in (m)					
		Soft soil		Medium soil		Hard soil	
		X	Y	X	Y	X	Y
Roof	6	0.24	0.1044	0.1962	0.0864	0.1458	0.066
Storey 9	6	0.2352	0.0918	0.1926	0.0762	0.1428	0.0582
Storey 8	6	0.2262	0.0792	0.1854	0.066	0.1374	0.0504
Storey 7	6	0.2136	0.0666	0.1752	0.0552	0.1296	0.042
Storey 6	6	0.201	0.054	0.1644	0.0444	0.1218	0.0342
Storey 5	6	0.1854	0.0414	0.1518	0.0348	0.1128	0.0264
Storey 4	6	0.168	0.03	0.1374	0.0252	0.102	0.0192
Storey 3	6	0.1476	0.0198	0.1206	0.0168	0.0894	0.0126
Storey 2	6	0.1254	0.0114	0.1026	0.0096	0.0762	0.0072
Storey 1	6	0.0954	0.0048	0.078	0.0036	0.0576	0.003

7.0 COMPARISON OF PERFORMANCE LEVEL OFBUILDINGS WITH DIFFERENT CODES OF PRACTICE

As described in analysis chapters, the selected three structures have been analysed as per three different codes of practice. In order to be more general, the structures were analysed for three different soil conditions, which can be commonly found in the country. In this way, totally 27 cases were analysed. The output of those analysis were tabulated in respective subsection of the analysis chapter.

This chapter presents a detail comparison and study on analysis output. The output values were compared under different criteria to find out possible varying patterns.

7.1 Comparison based on target performance level

The structural performance of a building can be identified by its target structural performance level. The FEMA 356 (Federal Emergency Management Agency) in United States (US) has defined minimum drift limits to be maintained in order to achieve different target performance levels. Therefore the percentage drift at roof level of the three structures were calculated and tabulated as below to find out the target performance level which has been achieved by the structure under different codes of practice and different possible soil conditions respectively.

Table 7.1.1- Transient lateral drift at roof level of the three structures

Soil Type	Transient lateral displacement at roof level (m)						Building height (m)	Transient lateral drift at roof level (%)					
	Euro Code		Australian Code		Indian Code			Euro Code		Australian Code		Indian Code	
	X	Y	X	Y	X	Y		X	Y	X	Y	X	Y
Building-A													
Soft / Very soft	0.1515	0.1595	0.2207	0.2275	0.1806	0.1830	71.2	0.21	0.22	0.31	0.32	0.25	0.26
Medium / Shallow	0.1253	0.1312	0.1074	0.1063	0.1548	0.1542	71.2	0.18	0.18	0.15	0.15	0.22	0.22
Hard / Rock	0.0954	0.0994	0.0811	0.0790	0.1248	0.1224	71.2	0.13	0.14	0.11	0.11	0.18	0.17
Building-B													
Soft / Very soft	0.1341	0.1464	0.1672	0.1721	0.1434	0.1530	46.3	0.29	0.32	0.36	0.37	0.31	0.33
Medium / Shallow	0.1101	0.1194	0.0715	0.0725	0.1194	0.1260	46.3	0.24	0.26	0.15	0.16	0.26	0.27
Hard / Rock	0.0822	0.0893	0.0520	0.0520	0.0912	0.0954	46.3	0.18	0.19	0.11	0.11	0.20	0.21
Building-C													
Soft / Very soft	0.2388	0.0980	0.1443	0.1196	0.2400	0.1044	31.6	0.76	0.31	0.46	0.38	0.76	0.33
Medium / Shallow	0.1948	0.0804	0.0595	0.0510	0.1962	0.0864	31.6	0.62	0.25	0.19	0.16	0.62	0.27
Hard / Rock	0.1450	0.0600	0.0426	0.0372	0.1458	0.0660	31.6	0.46	0.19	0.14	0.12	0.46	0.21

According to the results obtained and presented in Table 7.1.1, it can be clearly identified that in all twenty seven cases, the transient lateral drift at roof level has been maintained below 1%, which is the minimum drift to be maintained by a structure to achieve Immediate Occupancy Level (IOL), according to FEMA356 standards.

Based on values from Table 7.1.1, Table 7.1.2 has been prepared to determine the code of practice, which has given the maximum and the minimum values of the transient drift at roof level.

Table 7.1.2Code of practice for highest and lowest drift ratioat roof level

Soil Type	Code of practice for storey drift ratio at rooflevel											
	For highest storey drift ratio at roof level						For lowest storey drift ratio at roof level					
	Building - A		Building - B		Building - C		Building - A		Building - B		Building - C	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Soft / Very soft	AS	AS	AS	AS	EC/IS	AS	EC	EC	EC	EC	AS	EC
Medium / Shallow	IS	IS	IS	IS	EC/IS	IS	AS	AS	AS	AS	AS	AS
Hard / Rock	IS	IS	IS	IS	EC/IS	IS	AS	AS	AS	AS	AS	AS

According to the above table, for all three buildings, except in soft/very soft soil conditions, most of times, the highest drift ratio at roof level have been achieved, when they were analysed according only to Indian code (10 out of 18 occasions). At three occasions, both the Euro code and the Indian code have given highest values.In case of soft/very soft soil conditions, most of times (5 out of 6 occasions), the Australian code has given the highest drift values. The possible reason may be that, when analysing according to Australian code, to be more conservative, the "Very soft soil" condition was adopted instead of "Soft soil" condition, which was the soil condition adopted in the analysis according to Euro code and the Indian code.

Generally, it can be also noted that, in most of cases (13 out of 18 occasions), the lowest drift values have been achieved, when they were analysed according to the Australiancode.

7.2 Comparison based on higheststorey drift ratios

The highest drift ratio at individual floor levels is an important parameter to be considered in finding out the performance of a structure. The Table 7.2.1 presents the highest drift ratios achieved when the structures were analysed according to different codes of practice under different soil conditions.

Table 7.2.1 - Higheststorey drift ratio at any storey level

Soil Type	Highest storey drift ratio (%) at any storey level					
	Euro Code		Australian Code		Indian Code	
	X	Y	X	Y	X	Y
Building-A						
Soft / Very soft	0.31	0.28	0.44	0.43	0.38	0.32
Medium / Shallow	0.25	0.23	0.22	0.19	0.33	0.27
Hard / Rock	0.20	0.17	0.17	0.14	0.27	0.22
Building-B						
Soft / Very soft	0.36	0.38	0.45	0.45	0.38	0.40
Medium / Shallow	0.29	0.30	0.23	0.18	0.32	0.32
Hard / Rock	0.22	0.23	0.13	0.13	0.25	0.25
Building-C						
Soft / Very soft	2.07	0.40	1.27	0.49	2.07	0.42
Medium / Shallow	1.70	0.33	0.52	0.21	1.70	0.36
Hard / Rock	1.26	0.25	0.37	0.16	1.25	0.28

Based on values from Table 7.2.1, Table 7.2.2 has been prepared to determine the code of practice, which has given the maximum and the minimum values of the highest storey drift ratio at roof level.

Table 7.2.2 - Code of practice for maximum and minimum value of highest storey drift ratio at any storey level

Soil Type	Code of practice for highest storey drift ratio (At any floor level)											
	For maximum value of the highest storey drift ratio						For minimum value of the highest storey drift ratio					
	Building - A		Building - B		Building - C		Building - A		Building - B		Building - C	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Soft / Very soft	AS	AS	AS	AS	EC/IS	AS	EC	EC	EC	EC	AS	EC
Medium / Shallow	IS	IS	IS	IS	EC/IS	IS	AS	AS	AS	AS	AS	AS
Hard / Rock	IS	IS	IS	IS	EC	IS	AS	AS	AS	AS	AS	AS

The distribution of highest drift ratio at individual floor levels also follows almost the same pattern as lateral drift at roof level of the structures, which has been described in section 7.1.

According to the above table, for all three buildings, except in soft/very soft soil conditions, most of times, the highest drift ratio at any floor level have been achieved, when they were analysed according only to Indian code (10 out of 18 occasions). Only at one occasion the Euro code only has given highest drift ratio. At two occasions, both the Euro code and the Indian code have given highest values. In case of soft/very soft soil conditions, most of times (5 out of 6 occasions), the Australian code has given the highest drift values..

Generally, it can be also noted that, in most of cases (13 out of 18 occasions), the lowest drift values have been achieved, when they were analysed according to the Australian code.

7.3 Comparison based on design base shear force

The design base shear is also an important parameter, that can be used as a basis for a comparison of analysis results. The design base shear forces obtained by each analysis case are presented in Table 7.3.1

Table 7.3.1- Design base shear force of the three structures

Soil Type	Design base shear force (kN)					
	Euro Code		Australian Code		Indian Code	
	X	Y	X	Y	X	Y
Building-A						
Soft / Very soft	6,094	5,947	5,442	5,177	3,591	2,889
Medium / Shallow	5,420	5,267	3,395	3,159	2,917	2,328
Hard / Rock	4,730	4,584	2,589	2,362	2,160	1,739
Building-B						
Soft / Very soft	7,441	6,380	5,396	4,246	4,260	3,859
Medium / Shallow	6,326	5,618	2,624	2,441	3,459	3,131
Hard / Rock	5,061	4,803	1,886	1,761	2,549	2,294
Building-C						
Soft / Very soft	3,666	8,789	1,745	7,954	1,220	3,231
Medium / Shallow	3,004	7,461	720	4,066	1,000	2,628
Hard / Rock	2,225	6,012	515	3,039	741	2,001

Based on values from Table 7.3.1, Table 7.3.2 has been prepared to determine the code of practice, which has given the highest and the lowest values of the design base shear force.

Table 7.3.2 - Code of practice for highest and lowest design base shear force

Soil Type	Code of practice for design base shear force											
	For highest design base shear force						For lowest design base shear force					
	Building - A		Building - B		Building - C		Building - A		Building - B		Building - C	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Soft / Very soft	EC	EC	EC	EC	EC	EC	IS	IS	IS	IS	IS	IS
Medium / Shallow	EC	EC	EC	EC	EC	EC	IS	IS	AS	AS	AS	IS
Hard / Rock	EC	EC	EC	EC	EC	EC	IS	IS	AS	AS	AS	IS

According to the results presented in Table 7.3.2, it can be clearly stated that the Euro code has given the highest design base shear values at all eighteen occasions.

Further, the Indian code has given lowest base shear values at many occasions (12 out of 18 occasions). The reason seems to be that, the Indian code recommends to use a reduced zone factor (Z/2) to represent Design Basis Earthquake (DBE), which tends to give lower response quantities consequently (Refer Clause 6.4.2 of IS 1893 (Part1) :2002).

8.0 CONCLUSION AND RECOMMENDATIONS

According to Table 7.1.1 in previous chapter, it can be clearly concluded that, in all twenty seven cases, irrespective of the code of practice, which has been used in analysis procedure, the structures have achieved Immediate Occupancy Level (IOL), according to FEMA356 standards.

Referring to Tables 7.1.1,7.1.2, 7.2.1 and 7.2.2, Generally, it can be also concluded that the Indian code has given highest drift values at many occasions while the Euro code also has caused in very close or sometimes similar drift values as in case of Indian code. The Australian code has generally caused in giving lowest drift values.

As per Table 7.3.2, it can be clearly concluded that the Euro code has given the highest design base shear values at all eighteen occasions.Further,it has been noted that the Indian code has given lowest base shear values at many occasions. The reason for Indian code to produced lower design base shear forces at many occasions is mainly because it allows to use reduced values for zone factor, *Z* to represent Design Basis Earthquake (DBE) instead of Maximum Considered Earthquake (MCE). .

When the three codes of practice are compared, it has been noted that overall, the Euro code has describe the whole analysis process in detail and has considered the structural effects in many ways, like in case of regularity. The one who follows the code may feel it is easy to do so and also get much confident about his work. This will give many benefits, specially for beginners, who do not have an explicit knowledge at the start.

Another very important feature in Euro code is that, adopting nationally developed guidelines in analysis process is much easier with it.

Considering all above, as the main conclusion, it can be recommended to adopt the Euro code with recommendations provided by the research " Developing national guidelines for seismic analysis and design of (Engineered) buildings in Sri Lanka "conducted by the University of Moratuwa, Sri Lanka, for seismic analysis and design process of buildings in Sri Lanka.

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APPENDIX A : BASIC DETAILS OF BUILDING - A

A1. Eighteen storied residential apartment building

As the first case study, the selected building is a 18 storied reinforced concrete apartment building, which includes a ground floor and 17 above ground floors, where the ground floor up to fourth floor were used for parking purposes. Typical floor plan and a schematic cross section showing the dimension of the building in plan and elevation are given in Fig. A1 and A2 respectively. The total height of the building above the ground level is 71.2m and the plan dimension are29.49m x 19.38m

The main structural system consists of concrete frames and shear walls, whereas unreinforced masonry walls are used as partition walls.

At fifth floor level, the columns located at grid C1 and E1 on grid 1 have moved along grid 1 and the columns at grid A3, C1 and E1 on grid 8 have been shifted along grid 8 and also the columns grid H and K on grid 3 have been moved to grid 2. All the columns then continued up to roof level. Similarly, the shear walls located between grid E1 to H on grid 1 and C1 to J on grid 8 terminates at 5^{th} floor level. Also the shear wall between grids D1 to F1 have been moved from grid 3 to 2 from the fifth floor onwards.

The structure has been designed with C30 concrete, except the columns from ground floor up to sixth floor slab level, where C40 concrete was used.

All analysis were performed with the ETABS software (CSI 2002 ETABS Integrated Building Design Software, Computers & Structures Inc. Berkeley) on a three dimensional (spatial) mathematical model.

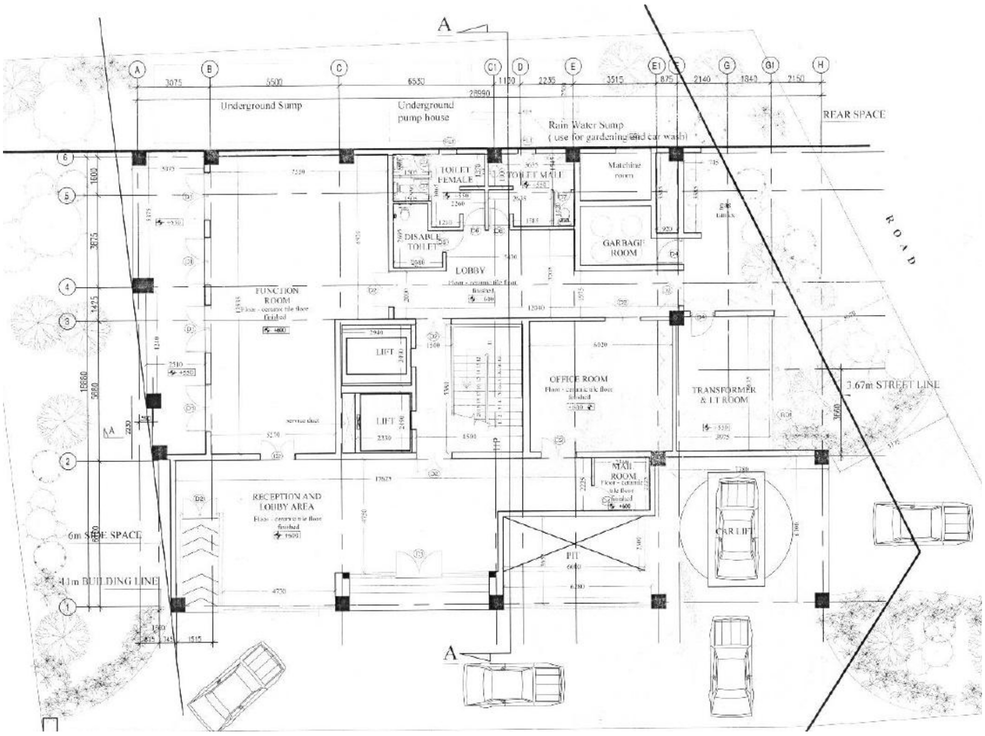

Figure A1: Plan View - Ground floor

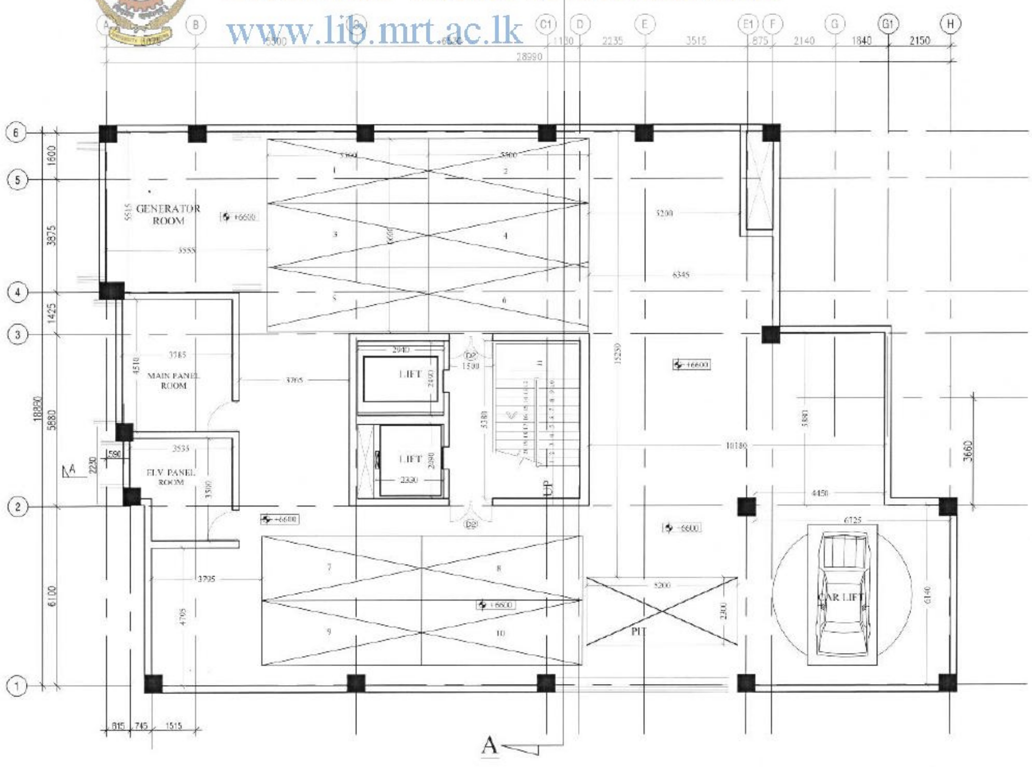

Figure A2: Plan View - First floor

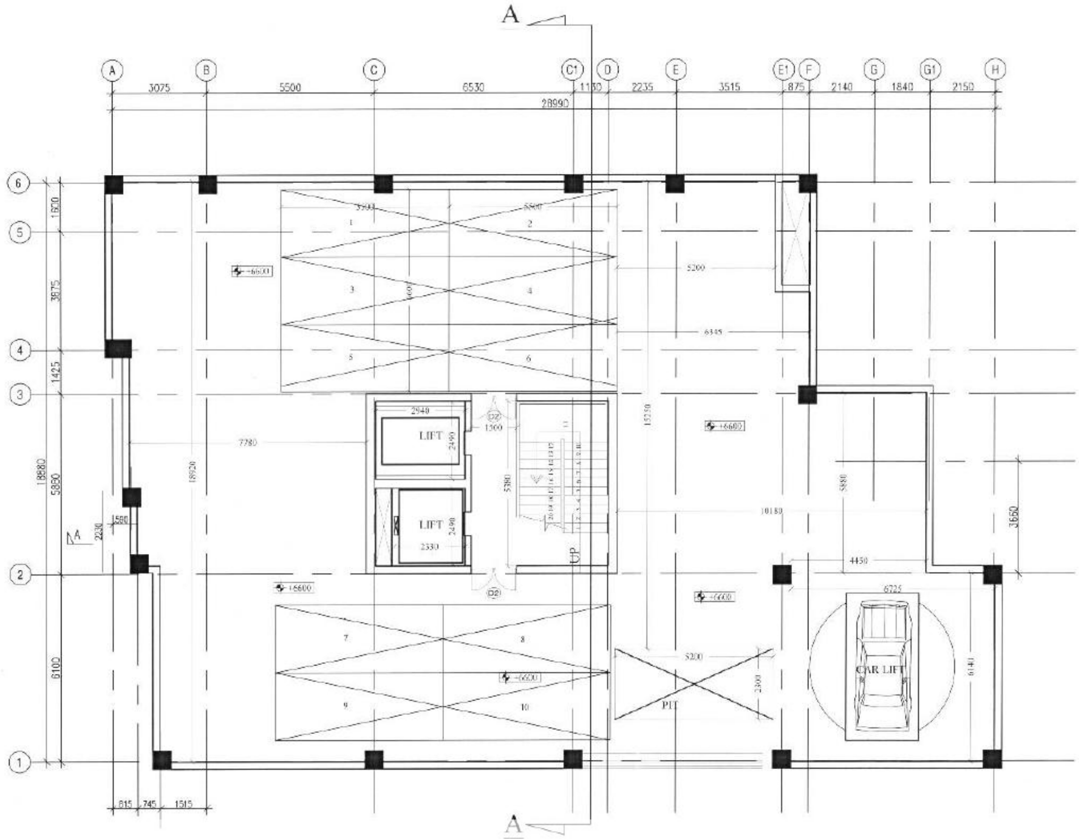

Figure A3: Plan View – 2nd to 4th floor

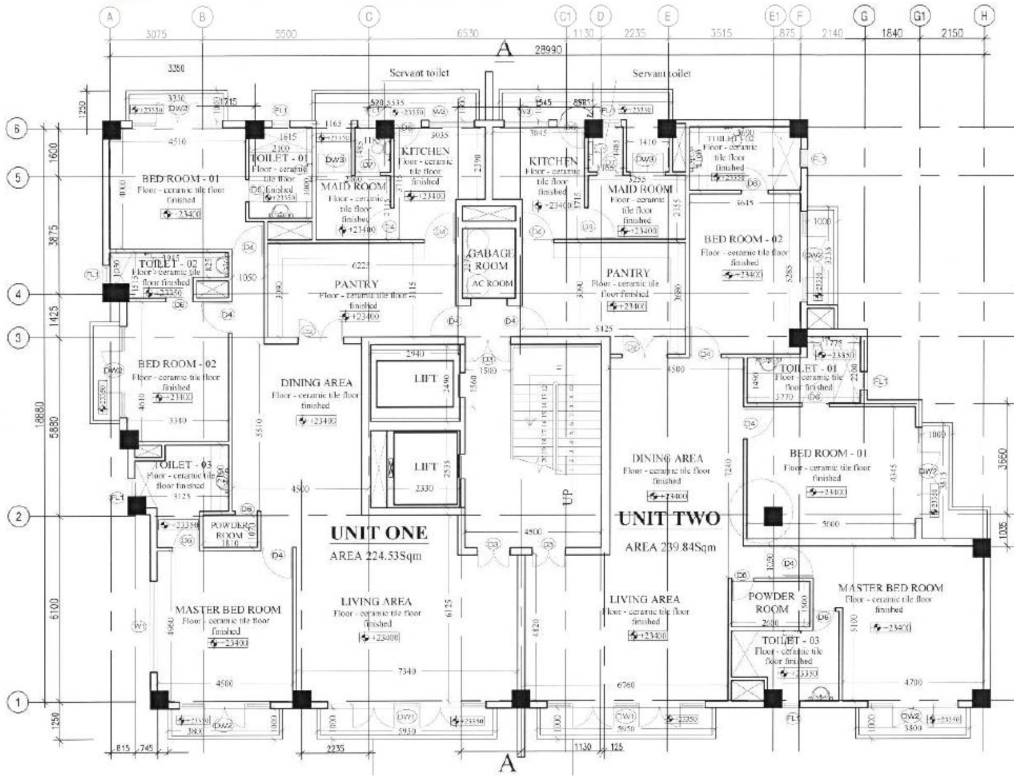

Figure A4: Plan View – 5th floor

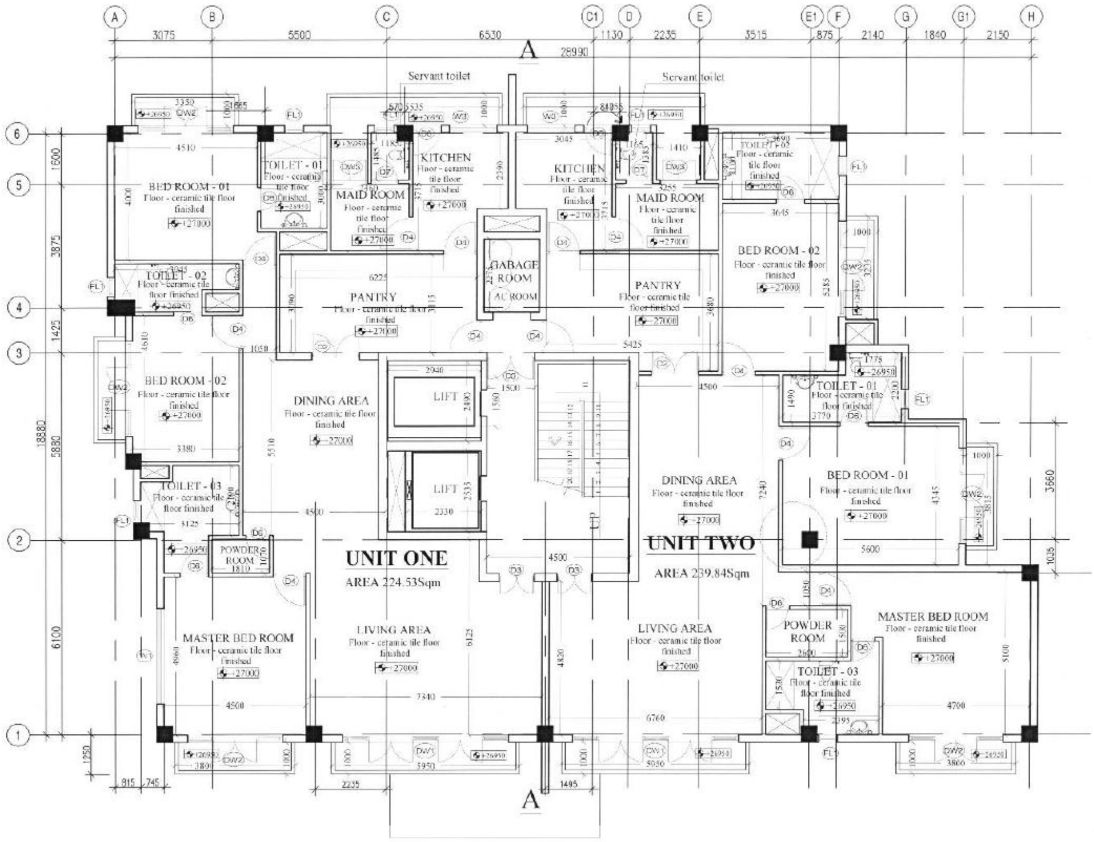

Figure A5: Plan View – 6th to 16th floor

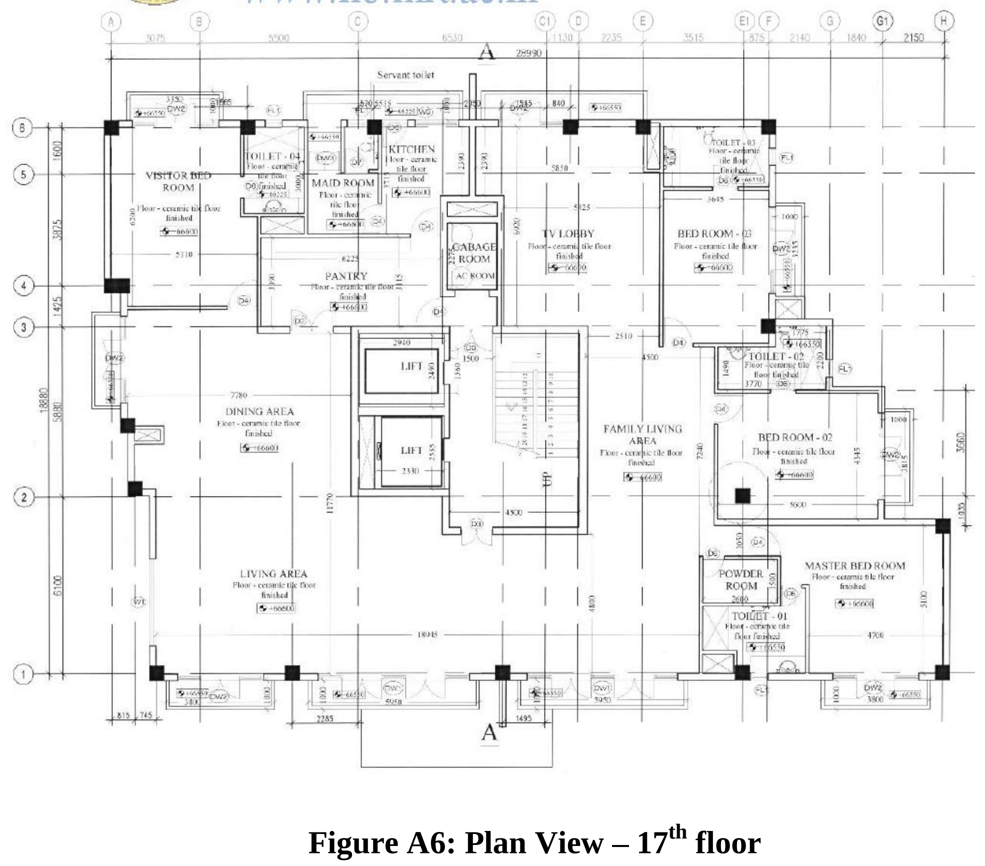

Figure A6: Plan View – 17th floor

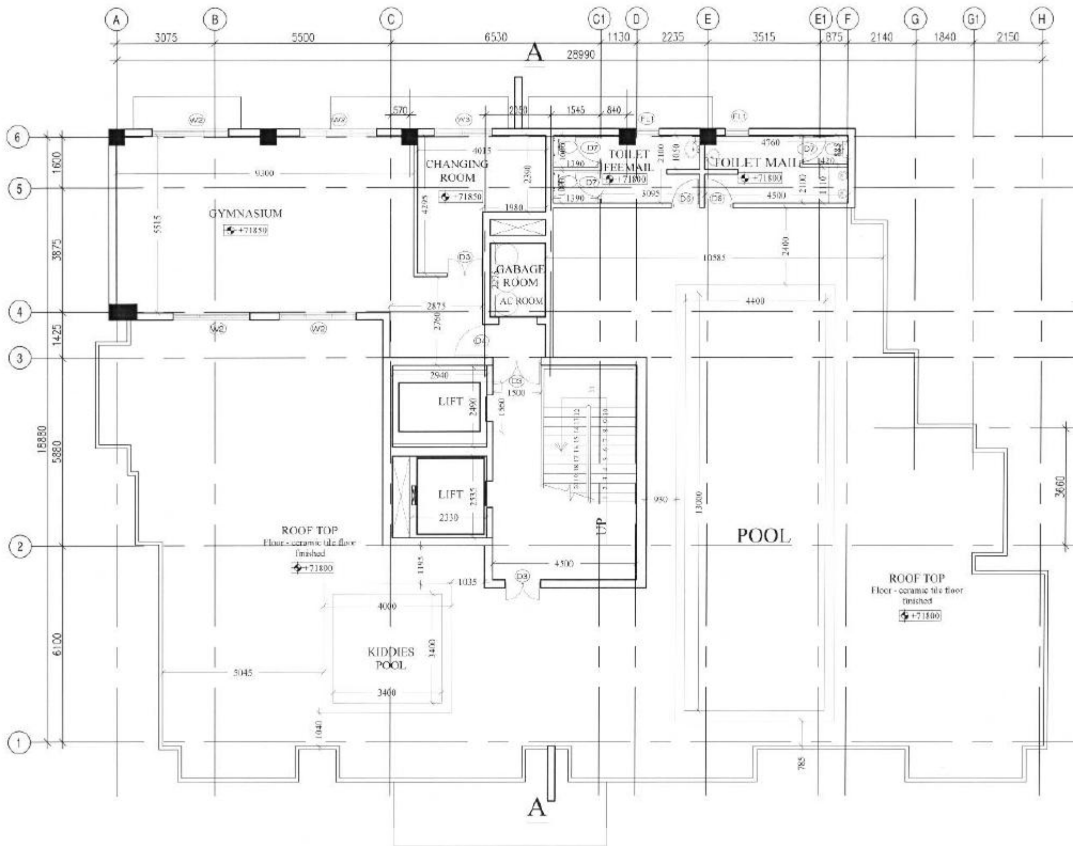

Figure A7: Plan View – Roof floor

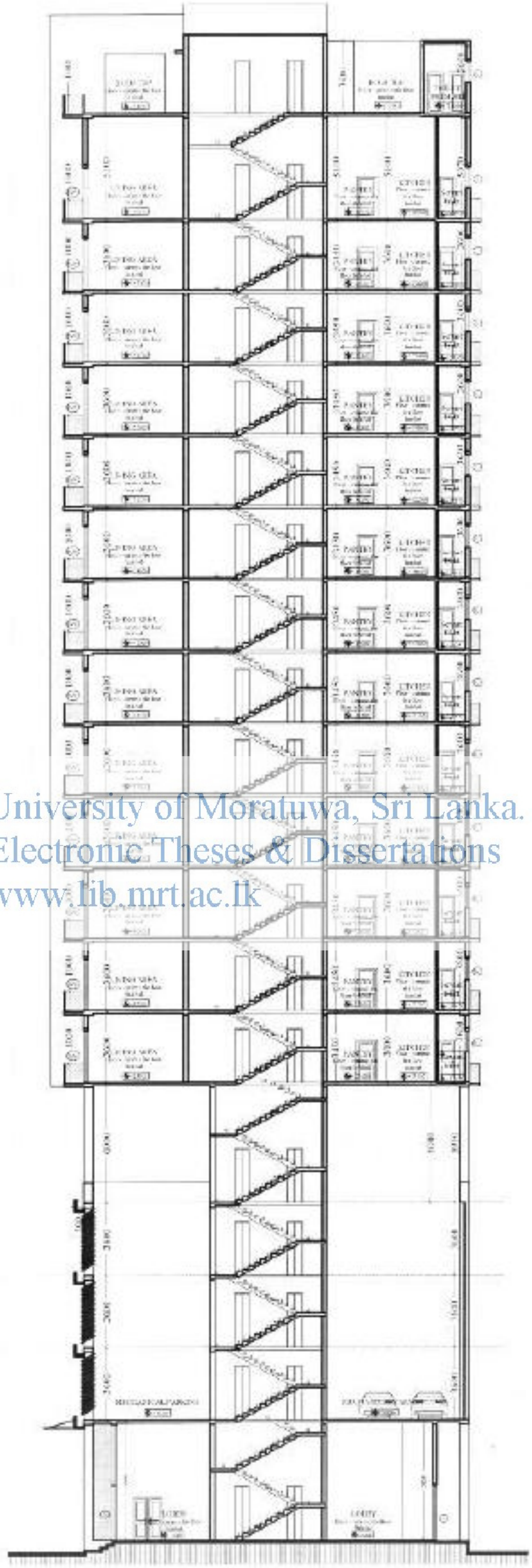

Figure A8: Cross section A-A of the buildings

Table A1 :Material properties used in the analysis

Material Properties			
Material	**Strength (N/mm^2)**	**Density (kN/m^3)**	**Modulus of elasticity (kN/mm^2)**
Concrete (C30)	30	24	26
Concrete (C40)	40	24	28
Steel	460	-	-
Masonry	-	22	-

Table A2 : Design loads used in the analysis

Live Load	
From first floor up to fourth floor	3.0 kN/m^2
From fifth floor up to roof floor	2.0 kN/m^2
Superimposed Dead Load	
Finishes -From first floor up to fourth floor	2.4 kN/m^2
Finishes -From fifth floor up to seventeenth floor	1.5 kN/m^2
Finishes –Roof floor	2.4 kN/m^2
Masonry walls-From first floor up to fourth floor	1.0 kN/m^2
Masonry walls-From fifth floor up to seventeenth floor	2.5 kN/m^2

Table A3 : Approximate calculation of dead load on the test buildings

Storey	Element	Dimensions (in mm)	No of Elements	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 1	Beam (X-dir)	500 x 300 x 78140	1	24	281	
	Beam (Y-dir)	500 x 300x 68320	1	24	246	
		500 x 250x 3320	1	24	10	
	Columns	600 x 600 x 4800	16	24	664	
		875 x 600 x 4800	1	24	60	
	Slab	13450 x 6000 x 125	1	24	242	
		14850 x 6000 x 150	1	24	321	
		25200 x 7000 x 165	1	24	699	
		13470 x 5000 x 175	1	24	283	
	Concrete Wall (X-direction)	3000 x 46920 x 250	1	24	845	
		1800 x 44820 x 250	1	24	484	
	Concrete Wall (Y-direction)	3000 x 30820 x 250	1	24	555	
		1800 x 27030 x 250	1	24	292	
	Finishes	18330 x 22300	1	2.4	981	
	Masonry Walls	18330 x 22300	1	1	409	6372
Storey (2-3)	Beam (X-dir)	500 x 300 x 735550	1	24	265	
		500 x 250 x 12070	1	24	43	
	Beam (Y-dir)	500 x 300x 75380	1	24	271	
		500 x 250x 3320	1	24	10	
	Columns	600 x 600 x 3600	16	24	498	
		875 x 600 x 3600	1	24	45	
	Slab	10980 x 6000 x 125	1	24	198	
		19760 x 6000 x 150	1	24	427	
		25200 x 7000 x 165	1	24	699	
		10550 x 5000 x 175	1	24	222	
	Concrete Wall (X-direction)	3600 x 44820 x 250	1	24	968	
	Concrete Wall (Y-direction)	3600 x 27030 x 250	1	24	584	
	Finishes	18330 x 22300	1	2.4	981	
	Masonry Walls	18330 x 22300	1	1	409	5620
Storey 4	Beam (X-dir)	500 x 300 x 735550	1	24	265	
		500 x 250 x 12070	1	24	43	
	Beam (Y-dir)	500 x 300x 75380	1	24	271	
		500 x 250x 3320	1	24	10	
	Columns	600 x 600 x 4800	16	24	664	
		875 x 600 x 4800	1	24	60	
	Slab	10980 x 6000 x 125	1	24	198	
		19760 x 6000 x 150	1	24	427	
		25200 x 7000 x 165	1	24	699	
		10550 x 5000 x 175	1	24	222	
	Concrete Wall (X-direction)	1800 x 44820 x 250	1	24	484	
		3000 x 42630 x 250	1	24	767	
	Concrete Wall (Y-direction)	1800 x 27030 x 250	1	24	292	
		3000 x 27030 x 250	1	24	487	
	Finishes	18330 x 22300	1	2.4	981	
	Masonry Walls	18330 x 22300	1	1	409	6279
Storey 5	Beam (X-dir)	500 x 300 x 57930	1	24	209	
		500 x 250x 1610	1	24	5	
		1500 x 600 x 18470	1	24	399	
		1800 x 600 x 20560	1	24	533	
	Beam (Y-dir)	500 x 300x 85000	1	24	306	
		500 x 250x 5540	1	24	17	
		1500 x 600 x 6350	1	24	137	
		1800 x 600 x 6350	1	24	165	
	Columns	600 x 600 x 4800	16	24	664	
		875 x 600 x 4800	1	24	60	
	Slab	16810 x 7100 x 125	1	24	358	
		27020 x 5000 x 150	1	24	486	
		14180 x 6350 x 165	1	24	357	
		7500 x 7030x 175	1	24	221	
	Concrete Wall (X-direction)	3000 x 42630 x 250	1	24	767	
		1800 x 44880 x 250	1	24	485	
	Concrete Wall (Y-direction)	3000 x 27030 x 250	1	24	487	
		1800 x 34680 x 250	1	24	375	
	Finishes	18330 x 22100	1	1.5	608	
	Masonry Walls	18330 x 22100	1	2.5	1013	7652

Table A3 : Approximate calculation of dead load on the test buildings (Contd.)

Storey	Element	Dimensions (in mm)	No of Elements	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 6	Beam (X-dir)	500 x 300 x 101660	1	24	366	
		500 x 250x 1610	1	24	5	
	Beam (Y-dir)	500 x 300x 89740	1	24	323	
		500 x 250x 9120	1	24	27	
	Columns	600 x 600 x 1800	16	24	249	
		500 x 500 x 1800	16	24	173	
		875 x 600 x 1800	1	24	23	
		875 x 500 x 1800	1	24	19	
	Slab	9330 x 6900 x 125	1	24	193	
		41380 x 5000 x 150	1	24	745	
		13640 x 6350 x 165	1	24	343	
		7500 x 7200x 175	1	24	227	
	Concrete Wall (X-direction)	3600 x 44880 x 250	1	24	969	
	Concrete Wall (Y-direction)	3600 x 34680 x 250	1	24	749	
	Finishes	18330 x 22100	1	1.5	608	
	Masonry Walls	18330 x 22100	1	2.5	1013	6032
Storey (7-16)	Beam (X-dir)	500 x 300 x 101660	1	24	366	
		500 x 250x 1610	1	24	5	
	Beam (Y-dir)	500 x 300x 89740	1	24	323	
		500 x 250x 9120	1	24	27	
	Columns	500 x 500 x 3600	16	24	346	
		875 x 500 x 3600	1	24	38	
	Slab	9330 x 6900 x 125	1	24	193	
		41380 x 5000 x 150	1	24	745	
		13640 x 6350 x 165	1	24	343	
		7500 x 7200x 175	1	24	227	
	Concrete Wall (X-direction)	3600 x 44880 x 250	1	24	969	
	Concrete Wall (Y-direction)	3600 x 34680 x 250	1	24	749	
	Finishes	18330 x 22100	1	1.5	608	
	Masonry Walls	18330 x 22100	1	2.5	1013	5952
Storey 17	Beam (X-dir)	500 x 300 x 101660	1	24	366	
		500 x 250x 1610	1	24	5	
	Beam (Y-dir)	500 x 300x 89740	1	24	323	
		500 x 250x 9120	1	24	27	
	Columns	500 x 500 x 4400	16	24	422	
		875 x 500 x 4400	1	24	46	
	Slab	9330 x 6900 x 125	1	24	193	
		41380 x 5000 x 150	1	24	745	
		13640 x 6350 x 165	1	24	343	
		7500 x 7200x 175	1	24	227	
	Concrete Wall (X-direction)	4400 x 44880 x 250	1	24	1185	
	Concrete Wall (Y-direction)	1800 x 34680 x 250	1	24	375	
		2600 x 29620 x 250	1	24	462	
	Finishes	18330 x 22100	1	1.5	608	
	Masonry Walls	18330 x 22100	1	2.5	1013	6340
Roof	Beam (X-dir)	500 x 300 x 94520	1	24	340	
		500 x 250x 1610	1	24	5	
		1300 x 300x 6920	1	24	65	
	Beam (Y-dir)	500 x 300 x 66810	1	24	241	
		500 x 250x 2220	1	24	7	
		1300 x 300x 26340	1	24	247	
	Columns	500 x 500 x 2600	16	24	250	
		875 x 500 x 2600	1	24	27	
	Slab	43190 x 5000 x 150	1	24	777	
		23490 x 6350 x 165	1	24	591	
		7500 x 7200x 175	1	24	227	
	Concrete Wall (X-direction)	2600 x 44880 x 250	1	24	700	
	Concrete Wall (Y-direction)	2600 x 29620 x 250	1	24	462	
	Finishes	18330 x 22100	1	2.4	972	4911

Table A4 : Approximate calculation of imposed load on the test buildings

Imposed Load				
Storey	**Area (m^2)**	**Load (kN/m^2)**	**Weight (kN)**	**Total (kN)**
Roof	405.09	2	811	811
Storey 17	405.09	2	811	811
Storey 7-16	405.09	2	811	8110
Storey 6	405.09	2	811	811
Storey 5	405.09	2	811	811
Storey 4	408.76	3	1227	1227
Storey 2-3	408.76	3	1227	2454
Storey 1	408.76	3	1227	1227
	Total Imposed Load (kN)			16,262

Table A5 : Fundamental period of vibration obtained from modal analysis

Mode	**Fundamental period (T_1)**
Translation in y-dir	1.64 (s)
Translation in x-dir	1.32(s)

A2. Basic calculations according to EN 1998-1:2004

A2.1Structural regularity

A2.1.1Criteria for regularity in plan

EN 1998-1: 2004

Clause 4.2.3.2 **Criteria for regularity in plan**

- *With respect to lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.*

  The building is approximately symmetrical in plan with respect to the lateral stiffness and the mass distribution in both X and Y directions.

- *The plan configuration shall be compact*.

The rectangular plan shape of the building fulfills the criteria of compact plan configuration.

- *The in-plan stiffness of the building shall be sufficiently large in comparison with the lateral stiffness of the vertical structural elements*

  The in-situ concrete floor slab of thickness 125mm, 150mm, 165mm and 175mm, connected to the lateral load resisting system proves that the lateral stiffness of the building is large in comparison with the vertical stiffness of the test building.

- *The slenderness of the building ($\lambda = L_{max}/L_{min}$) shall not be higher than 4.0.*

  The slenderness of the building amounts to $\lambda = 1.52$ (29.49m/19.38m) which can be considered as satisfied.

- *The structural eccentricity*

$e_{0x} \leq 0.30 r_x$

$e_{0y} \leq 0.30 r_y$

Refer Table A6

- *The torsional radius shall be larger than the radius of the gyration of the floor mass in plan*

$r_x \geq l_x$

$r_y \geq l_y$

According to Table A6, the selected building does not fulfill this requirement. The building was considered as torsionally flexible.

Table A6 :Structural eccentricity, torsional radius and radii of gyration in each horizontal direction

Level	Direction X				Direction Y			
	$e_{o,x}$	$0.3r_x$	r_x	l_s	$e_{o,y}$	$0.3r_y$	r_y	l_s
Storey 1	0.0049	0.281	0.9368	10.19	0.2246	0.2231	0.7435	10.19
Storey 2	0.0109	0.4108	1.3692	10.19	0.2449	0.3097	1.0322	10.19
Storey 3	0.0195	0.5346	1.7819	10.19	0.2711	0.3934	1.3112	10.19
Storey 4	0.0409	0.7747	2.5822	10.19	0.4263	0.5606	1.8686	10.19
Storey 5	0.0619	0.8217	2.7389	10.19	0.3355	0.6007	2.0022	10.19
Storey 6	0.0605	0.9009	3.0029	10.19	0.3625	0.6894	2.2979	10.19
Storey 7	0.0574	0.9804	3.2681	10.19	0.3686	0.7841	2.6138	10.19
Storey 8	0.0559	1.0566	3.5219	10.19	0.3702	0.8745	2.915	10.19
Storey 9	0.0544	1.1294	3.7646	10.19	0.3734	0.9596	3.1988	10.19
Storey 10	0.0529	1.1989	3.9963	10.19	0.3757	1.0397	3.4658	10.19
Storey 11	0.0514	1.2652	4.2173	10.19	0.3778	1.1151	3.7169	10.19
Storey 12	0.05	1.3286	4.4285	10.19	0.3795	1.1859	3.9531	10.19
Storey 13	0.0486	1.389	4.6301	10.19	0.3809	1.2527	4.1755	10.19
Storey 14	0.0473	1.4469	4.8231	10.19	0.3819	1.3156	4.3853	10.19
Storey 15	0.0461	1.5024	5.0079	10.19	0.3828	1.375	4.5834	10.19
Storey 16	0.0449	1.5562	5.1872	10.19	0.3829	1.4318	4.7728	10.19
Storey 17	0.0579	1.8271	6.0903	10.19	0.4825	1.688	5.6265	10.19
Roof	0.0228	1.271	4.2365	10.19	0.2835	1.1818	3.9394	10.19

A2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration

Structural eccentricities and torsional radii are calculated using the methods given in manual for the seismic design of steel and concrete buildings to Euro Code 8 [2]. Structural eccentricity (e_{0x} and e_{0y}) is the distance between the centre of mass and the centre of stiffness in two orthogonal axes X and Y. The torsional radii r_x (r_y) is defined as the square root of the ratio of the torsional stiffness to the lateral stiffness in Y (X) direction.

A2.1.1.1.1 Structural eccentricity

The structural eccentricity of level *i* is calculated using the equations;

$e_{ox,i}$ = (Rotation of the storey *i* about vertical axes due to static load ($F_{y,i}$) in Y direction) / (rotation of the floor due to torsional moment (M_i) about the vertical axis)

$e_{oy,i}$ = (Rotation of the storey *i* about vertical axes due to static load ($F_{x,i}$) in X direction) / (`rotation of the floor due to torsional moment (M_i) about the vertical axis)

In order to determine the structural eccentricity using the method above, computer analysis of the spatial model of the building is performed. In this analysis, static loads, F_{ix},F_{iy} and $M_i$of same magnitude are applied at the centre of mass of floor level i and the rotations of floors about vertical axis, $R_{z,i}$, due to each static load cases are obtained. The results obtained from the computer analysis for the test building including the eccentricities in both directions X and Y at tech floor level are shown in Table A2.

Table A7 :Structural eccentricity in each horizontal direction

Level	$F_{ix}=F_{iy}=M_i$	$R_{z,i}(F_x)$	$R_{z,i}(F_y)$	$R_{z,i}(M_i)$	$e_{o,y}$	$e_{o,x}$
Storey 1	10^6	1.294	0.0282	5.7613	0.2246	0.0049
Storey 2	10^6	1.4297	0.0634	5.8385	0.2449	0.0109
Storey 3	10^6	1.5862	0.114	5.8514	0.2711	0.0195
Storey 4	10^6	1.7486	0.1679	4.1018	0.4263	0.0409
Storey 5	10^6	1.9628	0.3624	5.8505	0.3355	0.0619
Storey 6	10^6	2.1578	0.35998	5.952	0.3625	0.0605
Storey 7	10^6	2.2066	0.3433	5.9857	0.3686	0.0574
Storey 8	10^6	2.2284	0.3366	6.0193	0.3702	0.0559
Storey 9	10^6	2.2589	0.3291	6.0502	0.3734	0.0544
Storey 10	10^6	2.2837	0.3213	6.0785	0.3757	0.0529
Storey 11	10^6	2.3063	0.3138	6.1041	0.3778	0.0514
Storey 12	10^6	2.3248	0.3062	6.1267	0.3795	0.05
Storey 13	10^6	2.3409	0.2988	6.1465	0.3809	0.0486
Storey 14	10^6	2.3538	0.2916	6.1633	0.3819	0.0473
Storey 15	10^6	2.3648	0.2845	6.1774	0.3828	0.0461
Storey 16	10^6	2.3682	0.2774	6.1844	0.3829	0.0449
Storey 17	10^6	2.3128	0.2774	4.7931	0.4825	0.0579
Roof	10^6	3.0682	0.2472	10.8244	0.2835	0.0228

A2.1.1.1.2 Torsional radius

The torsional radius r_x (r_y) is defined as the square root of the ratio of torsional stiffness (K_M) to the lateral stiffness in one direction K_y (K_x). It can be calculated from the computer analysis using the expression;

$$r_x\ (r_y) = \sqrt{\frac{\text{deflection at the centre of stiffness at each level due to static load in Y (X) direction}}{\text{rotation at each floor due to the moment applied at each floor level}}} \qquad (A.3)$$

The values correspond to each parameter in the above expression obtained from the computer analysis are given in Table A1.3. The torsional radii, r_x and r_y are also given in the table.

Table A8 : Torsional radii in each horizontal direction

level	$F_{ix}=F_{iy}=M_i$	$U_{x,i}$	$U_{y,i}$	$R_{z,i}(M_i)$	r_x	r_y
Storey 1	10^6	3.1852	5.0556	5.7613	0.9368	0.7435
Storey 2	10^6	6.2204	10.9462	5.8385	1.3692	1.0322
Storey 3	10^6	10.0607	18.5799	5.8514	1.7819	1.3112
Storey 4	10^6	14.3227	27.3488	4.1018	2.5822	1.8686
Storey 5	10^6	23.4534	43.8868	5.8505	2.7389	2.0022
Storey 6	10^6	31.429	53.6723	5.952	3.0029	2.2979
Storey 7	10^6	40.8953	63.9312	5.9857	3.2681	2.6138
Storey 8	10^6	51.1469	74.6623	6.0193	3.5219	2.915
Storey 9	10^6	61.9073	85.7442	6.0502	3.7646	3.1988
Storey 10	10^6	73.0138	97.0741	6.0785	3.9963	3.4658
Storey 11	10^6	84.3298	108.567	6.1041	4.2173	3.7169
Storey 12	10^6	95.7432	120.153	6.1267	4.4285	3.9531
Storey 13	10^6	107.1642	131.77	6.1465	4.6301	4.1755
Storey 14	10^6	118.523	143.373	6.1633	4.8231	4.3853
Storey 15	10^6	129.7709	154.926	6.1774	5.0079	4.5834
Storey 16	10^6	140.8766	166.406	6.1844	5.1872	4.7728
Storey 17	10^6	151.7357	177.787	4.7931	6.0903	5.6265
Roof	10^6	167.9795	194.274	10.8244	4.2365	3.9394

A2.1.1.1.3. Radius of gyration of the floor mass in plan (l_x and l_y)

The radius of gyration is defined as the square root of the ratio of the polar moment of inertia to the mass, the polar moment of inertia being calculated about the centre of mass. The manual for the seismic design of steel and concrete building to Euro code 8 gives an expression for the radius of gyration (l_s) applied to a rectangular building of side lengths of *l* and *b*, and a uniform mass distribution as,

$$l_s = \sqrt{\frac{l^2 + b^2}{12}} \qquad (A.4)$$

For the test building, the radius of gyration is calculated as shown in Table A9.

Table A9 :Radius of gyration

Level	*l* (m)	*b* (m)	l_s
Storey 1	29.49	19.38	10.19
Storey 2	29.49	19.38	10.19
Storey 3	29.49	19.38	10.19
Storey 4	29.49	19.38	10.19
Storey 5	29.49	19.38	10.19
Storey 6	29.49	19.38	10.19
Storey 7	29.49	19.38	10.19
Storey 8	29.49	19.38	10.19
Storey 9	29.49	19.38	10.19
Storey 10	29.49	19.38	10.19
Storey 11	29.49	19.38	10.19
Storey 12	29.49	19.38	10.19
Storey 13	29.49	19.38	10.19
Storey 14	29.49	19.38	10.19
Storey 15	29.49	19.38	10.19
Storey 16	29.49	19.38	10.19
Storey 17	29.49	19.38	10.19
Roof	29.49	19.38	10.19

A2.1.2Criteria for regularity in elevation

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Clause 4.2.3.3

In the case of investigated building, as mentioned under the description of the project, some of columns and shear walls terminates or shifts at fifth floor level. In order the building to be regular, all lateral load resisting system should run without interruption from foundation to the top. Since this requirement was not fulfilled, the building was considered as irregular in elevation.

Overall, the building was considered as torsionally fleixible

APPENDIX B : BASIC DETAILS OF BUILDING - B

B.1. Fourteen storied residential apartment building

The selected building is a 14 storied reinforced concrete apartment building, which includes the ground floor and 13 above ground floors. Typical floor plan and a schematic cross section showing the dimension of the building in plan and elevation are given in Fig. B1 and B2 respectively. The total height of the building above the ground level is 46.3m and the plan dimension are 44.3m x 20.6m

The main structural system consists of concrete frame with shear walls, whereas unreinforced masonry walls are used as partition walls.

At first floor level, the columns located at grid B'-1, B'-2, B, B'4 and B,-5 move on to grids B-1, B-2, B-4 and B-5 .

The structure has been designed with C30 concrete.

All analysis were performed with the ETABS software (CSI 2002 ETABS Integrated Building Design Software, Computers & Structures Inc. Berkeley) on a three dimensional (spatial) mathematical model.

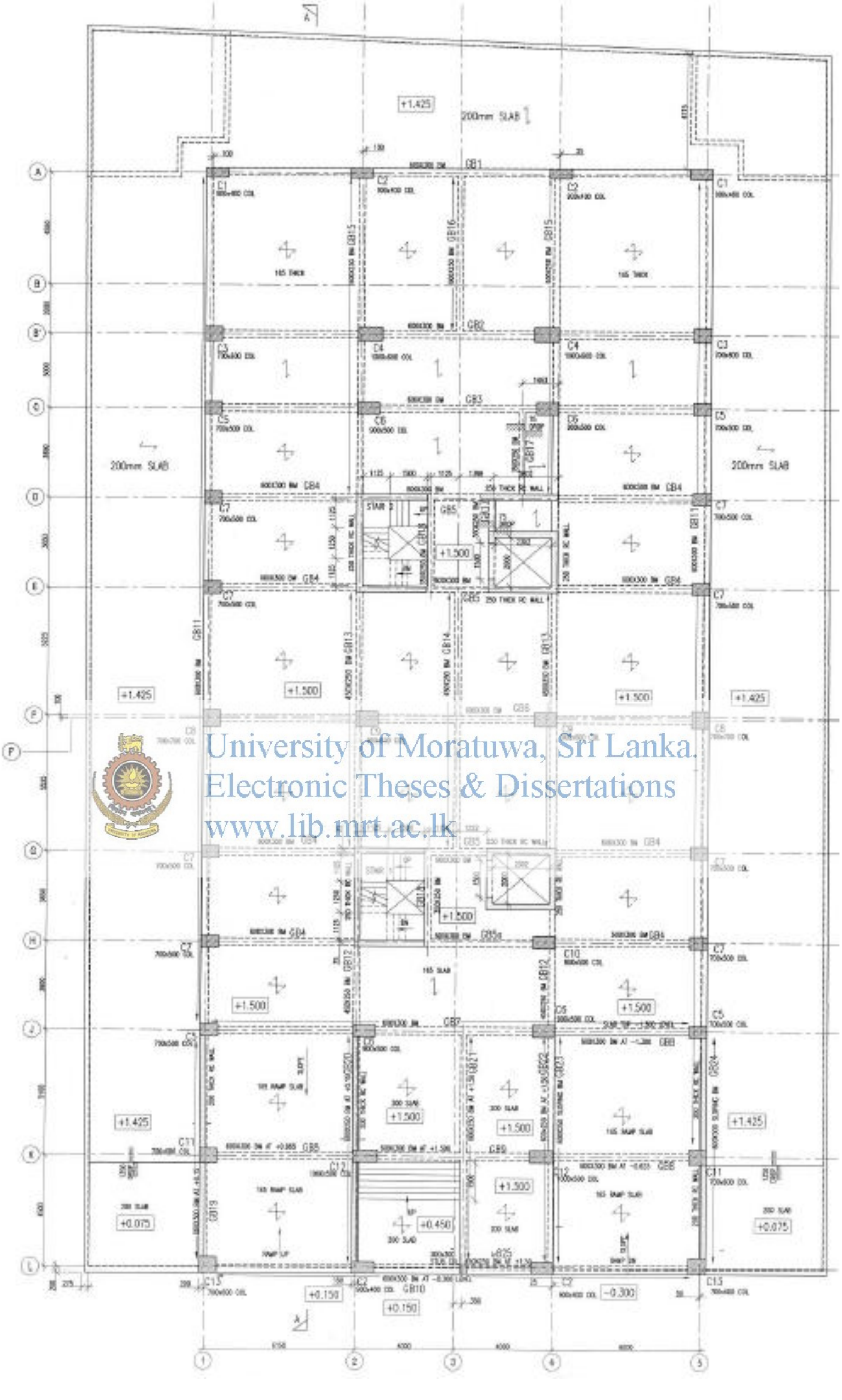

Figure B1: Plan View - Ground floor

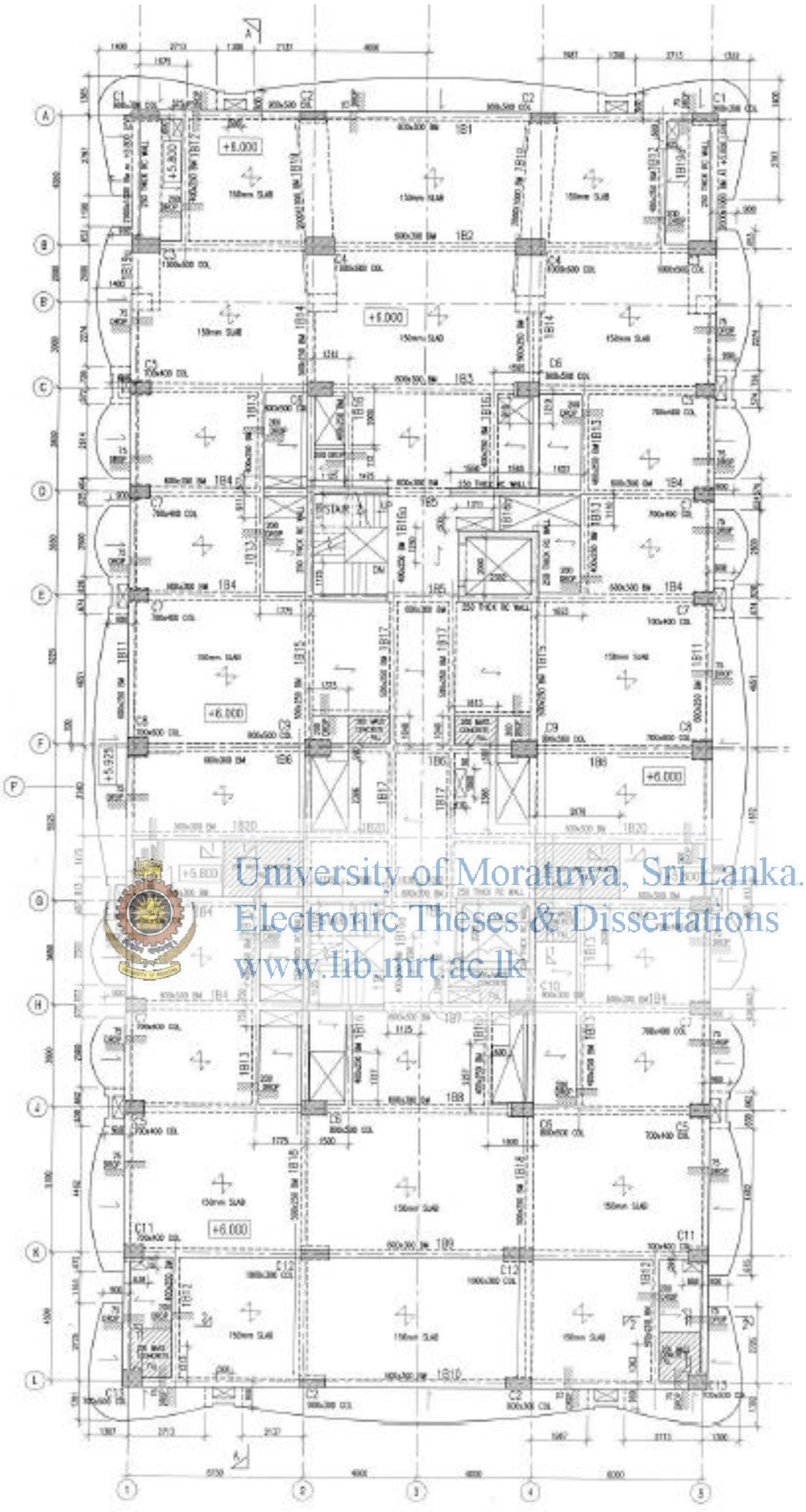

Figure B2 : Plan View - First floor

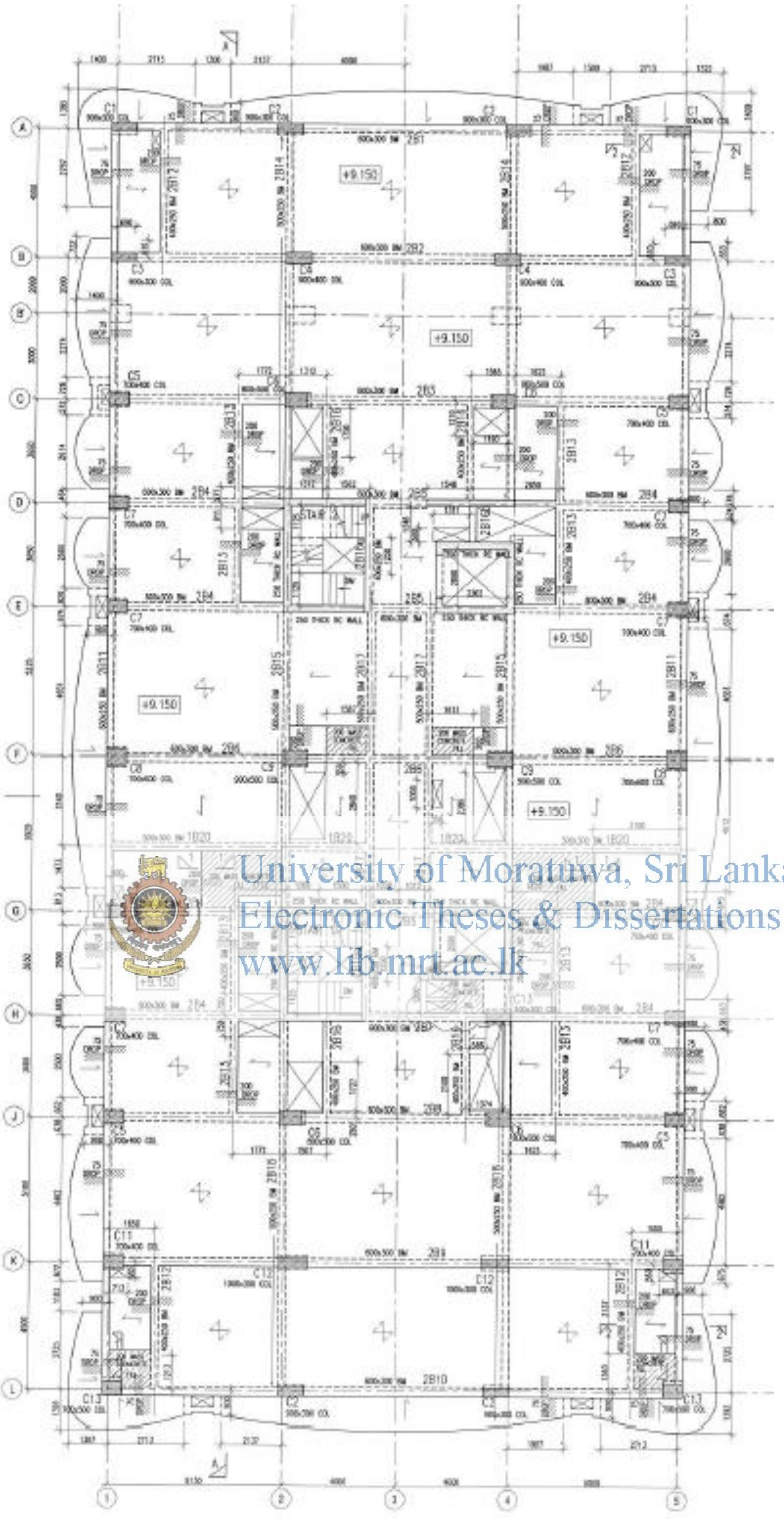

Figure B3 : Plan View – 2^{nd} to 13^{th} floor

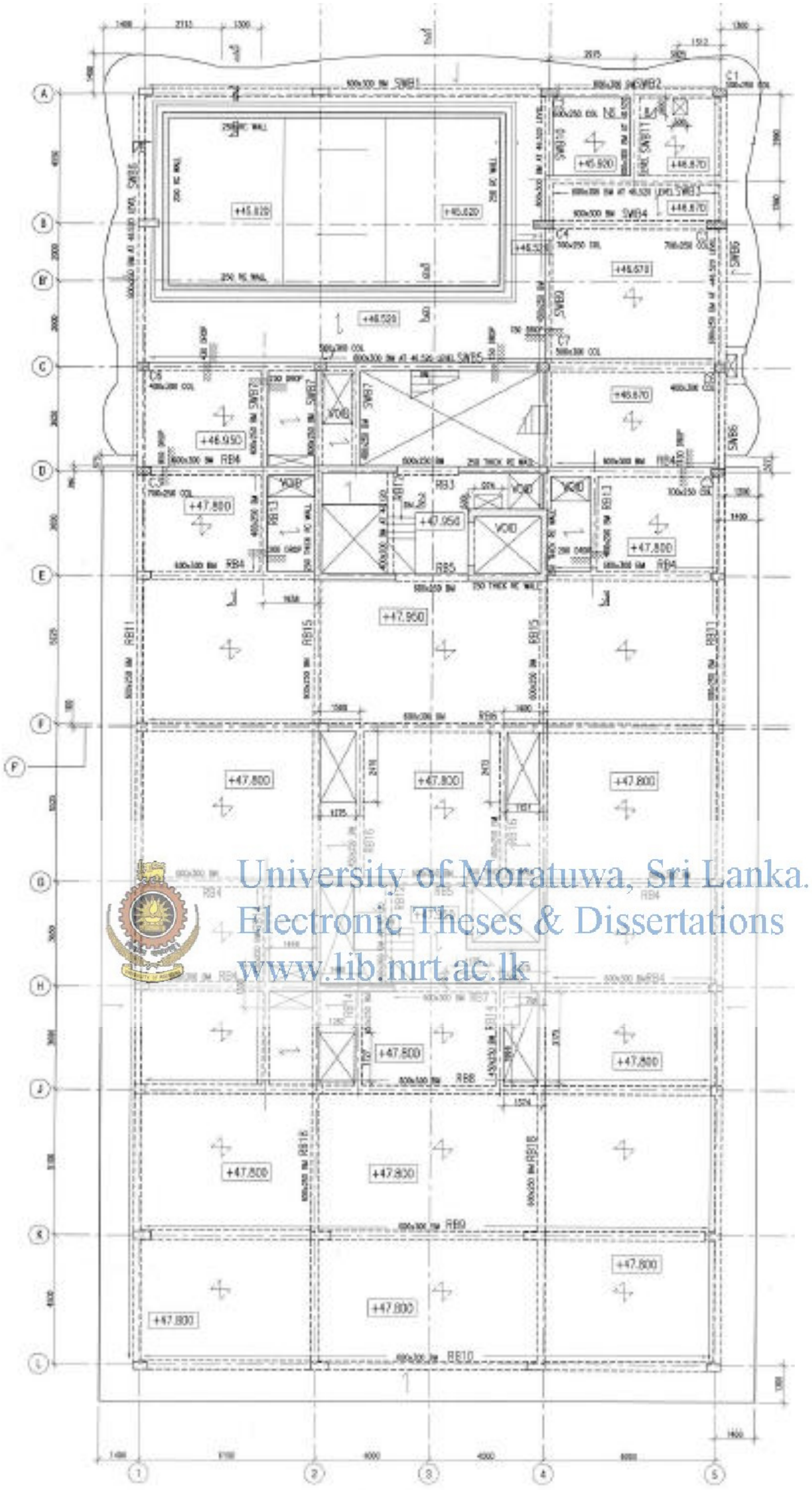

Figure B4 : Plan View – Roof floor

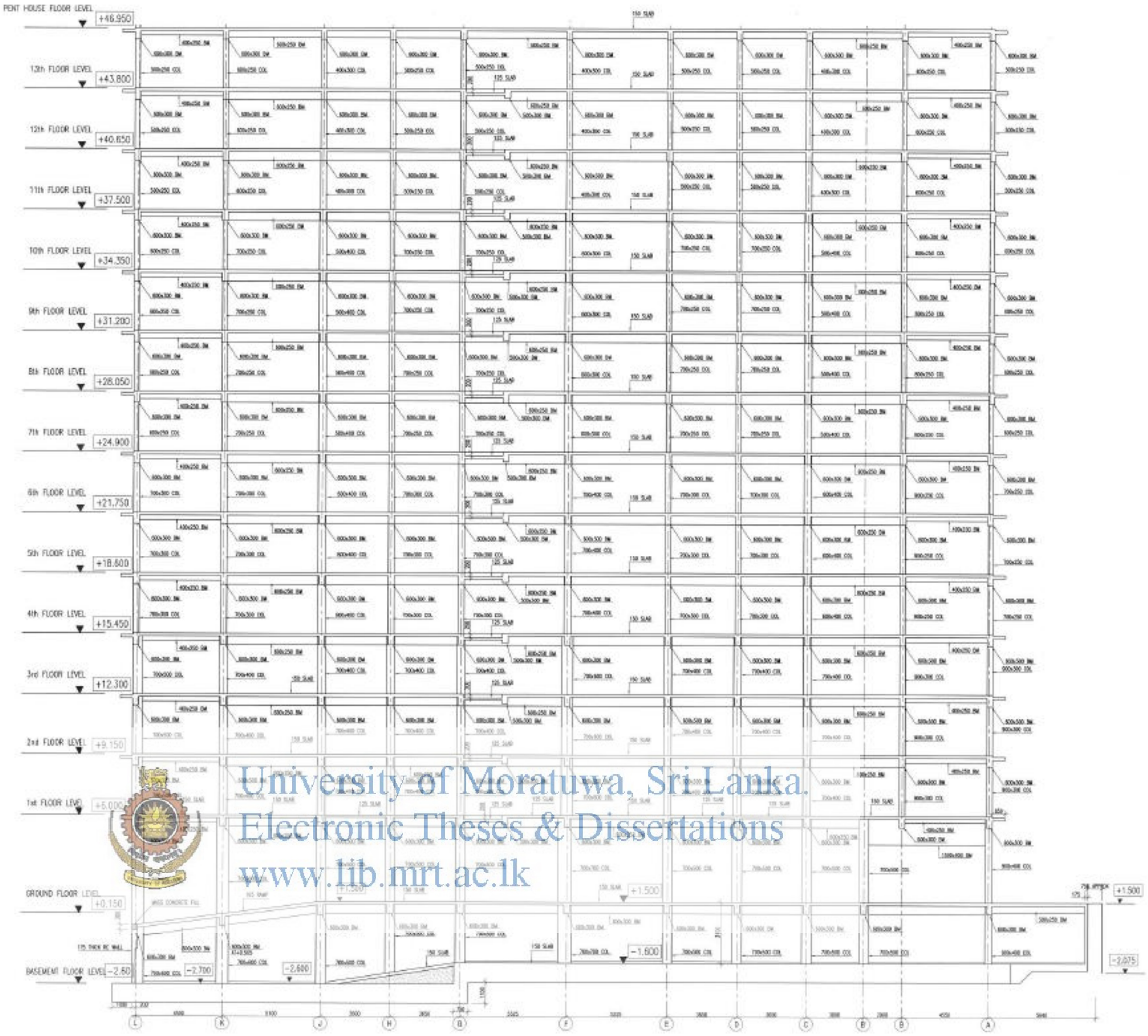

Figure B5 : Cross section A-A of the buildings

Table B1 : Material properties used in the analysis

Material Properties			
Material	**Strength (N/mm^2)**	**Density (kN/m^3)**	**Modulus of elasticity (kN/mm^2)**
Concrete (C30)	30	24	26
Concrete (C40)	40	24	28
Steel	460	-	-
Masonry	-	22	-

Table B2 : Design loads used in the analysis

Live Load	
From first floor up to roof floor	2.0 kN/m^2
Superimposed Dead Load	
Finishes -From first floor up to 13th floor	1.5 kN/m^2
Finishes –Roof floor	2.4 kN/m^2
Masonry walls-From first floor up to thirteenth floor	2.5 kN/m^2

Table B3 : Approximate calculation of dead load of the test building

Storey	Element	Dimensions (in mm)	No of Element	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 1	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 71800	1	24	216	
		400 x 250 x 70000	1	24	168	
		2000 x 1000 x 26200	1	24	1258	
	Columns	700 x 700 x 2250	2	24	53	
		700 x 600 x 2250	6	24	137	
		700 x 500 x 2250	12	24	227	
		900 x 400 x 2250	2	24	39	
		1000 x 600 x 2250	2	24	65	
		1000 x 500 x 2250	2	24	54	
		900 x 600 x 2250	2	24	59	
		900 x 500 x 2250	5	24	122	
		900 x 400 x 2250	4	24	78	
		700 x 600 x 1575	2	24	32	
		700 x 500 x 1575	2	24	27	
		700 x 400 x 1575	14	24	149	
		900 x 300 x 1575	2	24	21	
		900 x 300 x 1575	2	24	21	
		900 x 400 x 1575	2	24	28	
		1000 x 300 x 1575	2	24	23	
		900 x 500 x 1575	2	24	35	
		800 x 500 x 1575	4	24	61	
		900 x 300 x 1575	1	24	11	
		900 x 300 x 1575	4	24	41	
	Slab	109000 x 6000 x 150	1	24	2355	
		14000 x 13000 x 165	1	24	721	
		9500 x 7600 x 200	1	24	347	
	Concrete Wall	3825 x 24000 x 225	1	24	496	
	Concrete Wall	3825 x 16300 x 225	1	24	337	
	Finishes	44300 x 20600	1	2.4	2191	
	Masonry	44300 x 20600	1	1.5	1369	12023
Storey (2 -3)	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	700 x 600 x 3150	2	24	64	
		700 x 500 x 3150	2	24	53	
		700 x 400 x 3150	14	24	297	
		900 x 300 x 3150	2	24	41	
		900 x 300 x 3150	2	24	41	
		900 x 400 x 3150	2	24	55	
		1000 x 300 x 3150	2	24	46	
		900 x 500 x 3150	2	24	69	
		800 x 500 x 3150	4	24	121	
		900 x 300 x 3150	1	24	21	
		900 x 300 x 3150	4	24	82	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	10239

Table B3 : Approximate calculation of dead load of the test building (Contd.)

Storey	Element	Dimensions (in mm)	No of Element	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 4	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
		700 x 600 x 1575	2	24	32	
		700 x 500 x 1575	2	24	27	
		700 x 400 x 1575	14	24	149	
		900 x 300 x 1575	2	24	21	
		900 x 300 x 1575	2	24	21	
		900 x 400 x 1575	2	24	28	
		1000 x 300 x 1575	2	24	23	
		900 x 500 x 1575	2	24	35	
		800 x 500 x 1575	4	24	61	
		900 x 300 x 1575	1	24	11	
		900 x 300 x 1575	4	24	41	
		700 x 400 x 1575	2	24	22	
		700 x 300 x 1575	2	24	16	
		700 x 300 x 1575	2	24	16	
		900 x 250 x 1575	2	24	18	
		600 x 400 x 1575	4	24	37	
		700 x 300 x 1575	8	24	64	
		700 x 250 x 1575	2	24	14	
		900 x 300 x 1575	2	24	21	
		900 x 300 x 1575	2	24	21	
		800 x 500 x 1575	2	24	31	
		700 x 400 x 1575	4	24	43	
		900 x 250 x 1575	1	24	9	
		900 x 250 x 1575	4	24	35	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	10145
Storey (5-6)	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	700 x 400 x 3150	2	24	43	
		700 x 300 x 3150	2	24	32	
		700 x 300 x 3150	2	24	32	
		900 x 250 x 3150	2	24	35	
		600 x 400 x 3150	4	24	73	
		700 x 300 x 3150	8	24	128	
		700 x 250 x 3150	2	24	27	
		900 x 300 x 3150	2	24	41	
		900 x 300 x 3150	2	24	41	
		800 x 500 x 3150	2	24	61	
		700 x 400 x 3150	4	24	85	
		900 x 250 x 3150	1	24	18	
		900 x 250 x 3150	4	24	69	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	10034

Table B3 : Approximate calculation of dead load of the test building (Contd.)

Storey	Element	Dimensions (in mm)	No of Element	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 7	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	700 x 400 x 1575	2	24	22	
		700 x 300 x 1575	2	24	16	
		700 x 300 x 1575	2	24	16	
		900 x 250 x 1575	2	24	18	
		600 x 400 x 1575	4	24	37	
		700 x 300 x 1575	8	24	64	
		700 x 250 x 1575	2	24	14	
		900 x 300 x 3150	2	24	41	
		900 x 300 x 3150	2	24	41	
		800 x 500 x 3150	2	24	61	
		700 x 400 x 3150	4	24	85	
		900 x 250 x 3150	1	24	18	
		900 x 250 x 3150	4	24	69	
		600 x 300 x 1575	2	24	14	
		600 x 250 x 1575	2	24	12	
		700 x 250 x 1575	2	24	14	
		800 x 250 x 1575	2	24	16	
		500 x 400 x 1575	4	24	31	
		700 x 250 x 1575	8	24	53	
		600 x 250 x 1575	2	24	12	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	10003
Storey (8-10)	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	600 x 300 x 3150	2	24	28	
		600 x 250 x 3150	2	24	23	
		700 x 250 x 3150	2	24	27	
		800 x 250 x 3150	2	24	31	
		500 x 400 x 3150	4	24	61	
		700 x 250 x 3150	8	24	106	
		600 x 250 x 3150	2	24	23	
		900 x 300 x 3150	2	24	41	
		900 x 300 x 3150	2	24	41	
		800 x 500 x 3150	2	24	61	
		700 x 400 x 3150	4	24	85	
		900 x 250 x 3150	1	24	18	
		900 x 250 x 3150	4	24	69	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	9963

Table B3 : Approximate calculation of dead load of the test building (Contd.)

Storey	Element	Dimensions (in mm)	No of Element	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 11	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	600 x 300 x 1575	2	24	14	
		600 x 250 x 1575	2	24	12	
		700 x 250 x 1575	2	24	14	
		800 x 250 x 1575	2	24	16	
		500 x 400 x 1575	4	24	31	
		700 x 250 x 1575	8	24	53	
		600 x 250 x 1575	2	24	12	
		900 x 300 x 1575	2	24	21	
		900 x 300 x 1575	2	24	21	
		800 x 500 x 1575	2	24	31	
		700 x 400 x 1575	4	24	43	
		900 x 250 x 1575	1	24	9	
		900 x 250 x 1575	4	24	35	
		400 x 300 x 1575	2	24	10	
		500 x 250 x 1575	2	24	10	
		600 x 250 x 1575	2	24	12	
		600 x 250 x 1575	2	24	12	
		400 x 300 x 1575	4	24	19	
		500 x 250 x 1575	8	24	38	
		500 x 250 x 1575	2	24	10	
		700 x 250 x 1575	2	24	14	
		700 x 250 x 1575	2	24	14	
		500 x 300 x 1575	2	24	12	
		400 x 300 x 1575	4	24	19	
		700 x 250 x 1575	1	24	7	
		600 x 250 x 1575	4	24	23	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	[illegible]	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	9861
Storey 12	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	400 x 300 x 3150	2	24	19	
		500 x 250 x 3150	2	24	19	
		600 x 250 x 3150	2	24	23	
		600 x 250 x 3150	2	24	23	
		400 x 300 x 3150	4	24	37	
		500 x 250 x 3150	8	24	76	
		500 x 250 x 3150	2	24	19	
		700 x 250 x 3150	2	24	27	
		700 x 250 x 3150	2	24	27	
		500 x 300 x 3150	2	24	23	
		400 x 300 x 3150	4	24	37	
		700 x 250 x 3150	1	24	14	
		600 x 250 x 3150	4	24	46	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3150 x 24000 x 225	1	24	409	
	Concrete Wall	3150 x 16300 x 225	1	24	278	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	9739

Table B3 : Approximate calculation of dead load of the test building (Contd.)

Storey	Element	Dimensions (in mm)	No of Element	Density of (kN/m^3)	Weight (kN)	Total (kN)
Storey 13	Beam (X-dir)	600 x 300 x 208000	1	24	899	
		500 x 300 x 18300	1	24	66	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 98000	1	24	294	
		400 x 250 x 70000	1	24	168	
	Columns	400 x 300 x 3575	2	24	21	
		500 x 250 x 3575	2	24	22	
		600 x 250 x 3575	2	24	26	
		600 x 250 x 3575	2	24	26	
		400 x 300 x 3575	4	24	42	
		500 x 250 x 3575	8	24	86	
		500 x 250 x 3575	2	24	22	
		700 x 250 x 3575	2	24	31	
		700 x 250 x 3575	2	24	31	
		500 x 300 x 3575	2	24	26	
		400 x 300 x 3575	4	24	42	
		700 x 250 x 3575	1	24	16	
		600 x 250 x 3575	4	24	52	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	3575 x 24000 x 225	1	24	464	
	Concrete Wall	3575 x 16300 x 225	1	24	315	
	Finishes	44300 x 20600	1	1.5	1369	
	Masonry	44300 x 20600	1	2.5	2282	9884
Roof	Beam (X-dir)	600 x 300 x 208000	1	24	899	
	Beam (Y-dir)	600 x 250x 88000	1	24	317	
		500 x 250 x 75000	1	24	225	
		400 x 250 x 7000	1	24	17	
	Columns	400 x 300 x 2000	2	24	12	
		500 x 250 x 2000	2	24	12	
		600 x 250 x 2000	2	24	15	
		600 x 250 x 2000	2	24	15	
		400 x 300 x 2000	4	24	24	
		500 x 250 x 2000	8	24	48	
		500 x 250 x 2000	2	24	12	
		700 x 250 x 2000	2	24	17	
		700 x 250 x 2000	2	24	17	
		500 x 300 x 2000	2	24	15	
		400 x 300 x 2000	4	24	24	
		700 x 250 x 2000	1	24	9	
		600 x 250 x 2000	4	24	29	
	Slab	41250 x 22000 x 150	1	24	3267	
	Concrete Wall	2000 x 24000 x 225	1	24	260	
	Concrete Wall	2000 x 16300 x 225	1	24	177	
	Finishes	44300 x 20600	1	2.4	2191	7602

Table B4 : Approximate calculation of imposed load of the test buildings

Storey	Area (m^2)	Load (kN/m^2)	Weight (kN)	Total (kN)
Roof	44.3 x 20.6	2	1826	1826
Storey 13	44.3 x 20.6	2	1826	1826
Storey 12	44.3 x 20.6	2	1826	1826
Storey 11	44.3 x 20.6	2	1826	1826
Storey 8-10	44.3 x 20.6	2	1826	5478
Storey 7	44.3 x 20.6	2	1826	1826
Storey 5-6	44.3 x 20.6	2	1826	3652
Storey 4	44.3 x 20.6	2	1826	1826
Storey 2-3	44.3 x 20.6	2	1826	3652
Storey 1	44.3 x 20.6	2	1826	1826
	Total Imposed Load (kN)			25,564

Table B5 : Fundamental period of vibration obtained from modal analysis

Mode	Fundamental period (T_1)
Translation in y-dir	1.59 (s)
Translation in x-dir	1.44(s)

B2. Basic calculations according to EN 1998-1:2004

B2.1Structural regularity

B2.1.1Criteria for regularity in plan

EN 1998-1: 2004

Clause 4.2.3.2 **Criteria for regularity in plan**

- *With respect to lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.*
  The building is approximately symmetrical in plan with respect to the lateral stiffness and the mass distribution in both X and Y directions.

- *The plan configuration shall be compact*.
  The rectangular plan shape of the building fulfills the criteria of compact plan configuration.

- *The in-plan stiffness of the building shall be sufficiently large in comparison with the lateral stiffness of the vertical structural elements*

The in-situ concrete floor slab of thickness 150mmconnected to the lateral load resisting system proves that the lateral stiffness of the building is large in comparison with the vertical stiffness of the test building.

- *The slenderness of the building ($\lambda = L_{max}/L_{min}$) shall not be higher than 4.0.*

  The slenderness of the building amounts to λ = 2.15 (44.3/20.6m) which can be considered as satisfied.

- *The structural eccentricity*

$e_{0x} \leq 0.30 r_x$

  $e_{0y} \leq 0.30 r_y$

  Refer Table B6

- *The torsional radius shall be larger than the radius of the gyration of the floor mass in plan*

$r_x \geq l_s$

$r_y \geq l_s$

According to Table B6, the selected building does not fulfill this requirement. The building was considered as torsionally flexible.

Table B6 : Structural eccentricity, torsional radius and radii of gyration in each horizontal direction

Level	Direction X				Direction Y			
	$e_{o,x}$	$0.3r_x$	r_x	l_s	$e_{o,y}$	$0.3r_y$	r_y	l_s
Storey 1	1.2912	4.9487	16.4955	14.1	0.2494	3.9207	13.0689	14.1
Storey 2	1.3322	4.8081	16.0271	14.1	0.2534	3.8673	12.891	14.1
Storey 3	1.3656	4.6968	15.656	14.1	0.2567	3.8257	12.7524	14.1
Storey 4	1.3994	4.5887	15.2957	14.1	0.2607	3.7866	12.622	14.1
Storey 5	1.4353	4.482	14.9401	14.1	0.2655	3.7474	12.4913	14.1
Storey 6	1.4707	4.3763	14.5875	14.1	0.2704	3.7085	12.3615	14.1
Storey 7	1.5059	4.2714	14.238	14.1	0.276	3.6701	12.2337	14.1
Storey 8	1.5393	4.1648	13.8826	14.1	0.2823	3.6302	12.1005	14.1
Storey 9	1.5731	4.0538	13.5127	14.1	0.2897	3.5852	11.9507	14.1
Storey 10	1.6056	3.9378	13.126	14.1	0.2974	3.535	11.7833	14.1
Storey 11	1.6352	3.8135	12.7115	14.1	0.3064	3.4748	11.5827	14.1
Storey 12	1.6712	3.6785	12.2615	14.1	0.3183	3.3899	11.2995	14.1
Storey 13	1.7019	3.5287	11.7623	14.1	0.3321	3.272	10.9068	14.1
Roof	1.7405	3.3389	11.1296	14.1	0.3435	3.0541	10.1802	14.1

B2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration

Structural eccentricities and torsional radii are calculated using the same method as described in A2.1.1.1 under the building A. The results are tabulated as below.

Table B7 : Structural eccentricity in each horizontal direction

Level	$F_{ix}=F_{iy}=M_i$	$R_{z,i}(F_x)$	$R_{z,i}(F_y)$	$R_{z,i}(M_i)$	$e_{o,y}$	$e_{o,x}$
Roof	10^6	0.1163	0.6021	0.4663	0.2494	1.2912
Storey 13	10^6	0.1139	0.5987	0.4494	0.2534	1.3322
Storey 12	10^6	0.1113	0.592	0.4335	0.2567	1.3656
Storey 11	10^6	0.1079	0.5792	0.4139	0.2607	1.3994
Storey 10	10^6	0.1038	0.5612	0.3910	0.2655	1.4353
Storey 9	10^6	0.0984	0.5352	0.3639	0.2704	1.4707
Storey 8	10^6	0.0917	0.5004	0.3323	0.276	1.5059
Storey 7	10^6	0.0837	0.4564	0.2965	0.2823	1.5393
Storey 6	10^6	0.0745	0.4046	0.2572	0.2897	1.5731
Storey 5	10^6	0.0638	0.3444	0.2145	0.2974	1.6056
Storey 4	10^6	0.0519	0.277	0.1694	0.3064	1.6352
Storey 3	10^6	0.0395	0.2074	0.1241	0.3183	1.6712
Storey 2	10^6	0.0264	0.1353	0.0795	0.3321	1.7019
Storey 1	10^6	0.0135	0.0684	0.0393	0.3435	1.7405

Table B8 : Torsional radii in each horizontal direction

Level	$F_{ix}=F_{iy}=M_i$	$U_{x,i}$	$U_{y,i}$	$R_{z,i}(M_i)$	r_x	r_y
Roof	10^6	79.6421	126.8809	0.4663	16.4955	13.0689
Storey 13	10^6	74.6807	115.4358	0.4494	16.0271	12.891
Storey 12	10^6	70.4974	106.2549	0.4335	15.656	12.7524
Storey 11	10^6	65.9404	96.8351	0.4139	15.2957	12.622
Storey 10	10^6	61.0086	87.2732	0.3910	14.9401	12.4913
Storey 9	10^6	55.6067	77.4363	0.3639	14.5875	12.3615
Storey 8	10^6	49.7329	67.3638	0.3323	14.238	12.2337
Storey 7	10^6	43.4145	57.1436	0.2965	13.8826	12.1005
Storey 6	10^6	36.7331	46.9626	0.2572	13.5127	11.9507
Storey 5	10^6	29.7825	36.9567	0.2145	13.126	11.7833
Storey 4	10^6	22.7264	27.3721	0.1694	12.7115	11.5827
Storey 3	10^6	15.8448	18.6578	0.1241	12.2615	11.2995
Storey 2	10^6	9.4571	10.9989	0.0795	11.7623	10.9068
Storey 1	10^6	4.0729	4.8680	0.0393	11.1296	10.1802

Table B9 : Radius of gyration

Level	*l* (m)	*b* (m)	l_s
Roof	44.3	20.6	14.1
Storey 13	44.3	20.6	14.1
Storey 12	44.3	20.6	14.1
Storey 11	44.3	20.6	14.1
Storey 10	44.3	20.6	14.1
Storey 9	44.3	20.6	14.1
Storey 8	44.3	20.6	14.1
Storey 7	44.3	20.6	14.1
Storey 6	44.3	20.6	14.1
Storey 5	44.3	20.6	14.1
Storey 4	44.3	20.6	14.1
Storey 3	44.3	20.6	14.1
Storey 2	44.3	20.6	14.1
Storey 1	44.3	20.6	14.1

B2.1.2 Criteria for regularity in elevation

EN 1998-1: 2004

Clause 4.2.3.3

In the case of investigated building, as mentioned under the description of the project, some of columns discontinue at the first floor level. In order the building to be regular, all lateral load resisting system should run without interruption from foundation to the top. Since this requirement was not fulfilled, the building was considered as irregular in elevation.

Overall, the building was considered as torsionally flexible.

APPENDIX C : BASIC DETAILS OF BUILDING - C

C1. Ten storied residential apartment building

The selected building is a 10 storied reinforced concrete apartment building, which includes the ground floor and 9 above ground floors. Typical floor plan and a schematic cross section showing the dimension of the building in plan and elevation are given in Fig. C1 and C2 respectively. The total height of the building above the ground level is 31.46m and the plan dimensions are 41.3m x 25.6m

The main structural system consists of concrete frame shear walls, whereas unreinforced masonry walls are used as partition walls..

The structure has been designed with C25 concrete.

All analysis was performed with the ETABS software (CSI 2002 ETABS Integrated Building Design Software, Computers & Structures Inc. Berkeley) on a three dimensional (spatial) mathematical model.

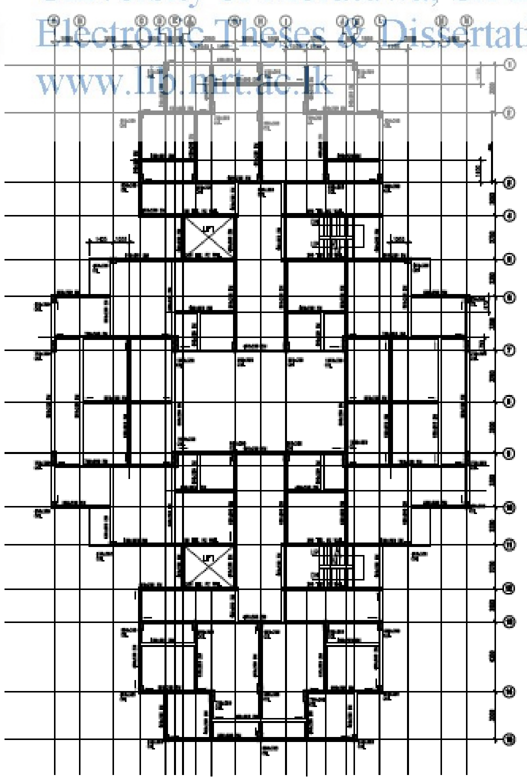

Figure C1: Plan View - First Floor

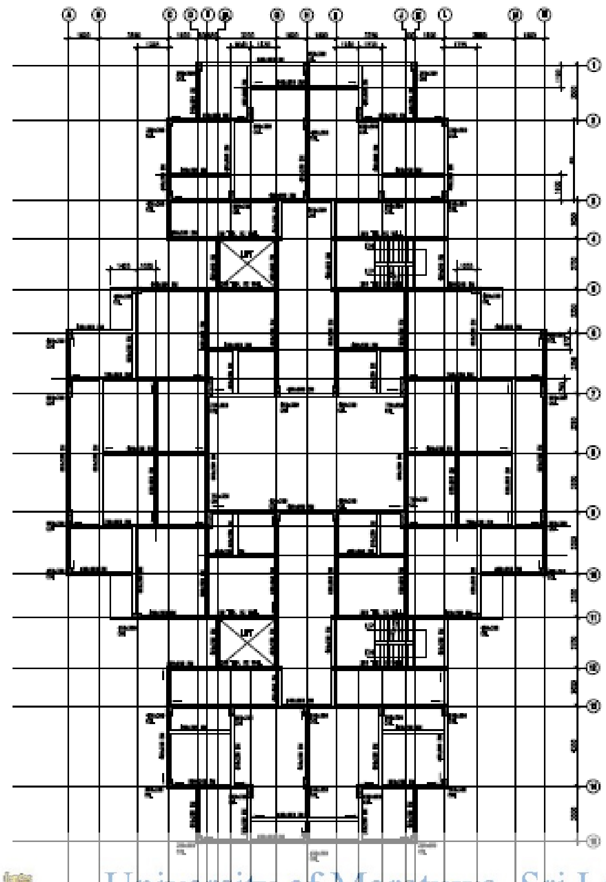

Figure C2: Plan View - Typical Floor

Table C1 :Material properties used in the analysis

Material	Strength (N/mm^2)	Density (kN/m^3)	Modulus of elasticity (kN/mm^2)
Concrete (C25)	25	24	24
Steel	460	-	-
Masonry	-	22	-

Table C2 : Design loads used in the analysis

Live Load	
From first floor up to roof floor	2.0 kN/m^2
Superimposed Dead Load	
Finishes -From first floor up to 9th floor	1.5 kN/m^2
Finishes –Roof floor	2.4 kN/m^2
Masonry walls-From first floor up to 9th floor	2.5 kN/m^2

Table C3 : Approximate calculation of dead load on the test building

Storey	Element	Dimensions (mm)	No of Elements	Density of Mat. (kN/m3) or	Weight (kN)	Total (kN)
Storey 1	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 131600	1.00	24.00	379	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	1000 x 350 x 3795	4.00	24.00	128	
		750 x 350 x 3795	8.00	24.00	191	
		600 x 300 x 3795	18.00	24.00	295	
		450 x 300 x 3795	16.00	24.00	197	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	3795 x 43600 x 250	1.00	24.00	993	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	8195
Storey 2	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 131600	1.00	24.00	379	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	1000 x 350 x 2985	4.00	24.00	100	
		750 x 350 x 2985	8.00	24.00	150	
		600 x 300 x 2985	18.00	24.00	232	
		450 x 300 x 2985	16.00	24.00	155	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	7809
Storey 3	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 131600	1.00	24.00	379	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	1000 x 350 x 1495	4.00	24.00	50	
		750 x 350 x 1495	8.00	24.00	75	
		600 x 300 x 1495	18.00	24.00	116	
		450 x 300 x 1495	16.00	24.00	78	
		750 x 350 x 1495	4.00	24.00	38	
		600 x 300 x 1495	12.00	24.00	78	
		450 x 300 x 1495	22.00	24.00	107	
		300 x 300 x 1495	8.00	24.00	26	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	7740
Storey 4-6	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 131600	1.00	24.00	379	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	750 x 350 x 2985	4.00	24.00	75	
		600 x 300 x 2985	12.00	24.00	155	
		450 x 300 x 2985	22.00	24.00	213	
		300 x 300 x 2985	8.00	24.00	52	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	7667

Table C3 : Approximate calculation of dead load on the test building (Contd.)

Storey	Element	Dimensions (mm)	No of Elements	Density of Mat. (kN/m3) or	Weight (kN)	Total (kN)
Storey 7	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 131600	1.00	24.00	379	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	750 x 350 x 1495	4.00	24.00	38	
		600 x 300 x 1495	12.00	24.00	78	
		450 x 300 x 1495	22.00	24.00	36	
		300 x 300 x 1495	8.00	24.00	26	
		600 x 350 x 1495	4.00	24.00	30	
		450 x 300 x 1495	4.00	24.00	19	
		300 x 300 x 1495	34.00	24.00	110	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	7509
Storey 8	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 117700	1.00	24.00	339	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	600 x 350 x 2985	4.00	24.00	60	
		450 x 300 x 2985	4.00	24.00	39	
		300 x 300 x 2985	34.00	24.00	219	
	Slab	29790 x 25600 x 125	1.00	24.00	2288	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	29790 x 25600	1.00	1.50	1144	
	Masonry Walls	29790 x 25600	1.00	2.50	1907	7450
Storey 9	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 117700	1.00	24.00	339	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	600 x 350 x 2985	4.00	24.00	60	
		450 x 300 x 2985	4.00	24.00	39	
		300 x 300 x 2985	34.00	24.00	219	
	Slab	28500 x 25600 x 125	1.00	24.00	2189	
	Concrete Wall	2985 x 43600 x 250	1.00	24.00	781	
	Finishes	28500 x 25600	1.00	1.50	1094	
	Masonry Walls	28500 x 25600	1.00	2.50	1824	7218
Roof	Beam (X-dir)	400 x 200 x 108000	1.00	24.00	207	
		600 x 200 x 117700	1.00	24.00	339	
	Beam (Y-dir)	400 x 200x 127400	1.00	24.00	245	
		600 x 200x 41800	1.00	24.00	120	
		700 x 200x 30000	1.00	24.00	101	
	Columns	600 x 350 x 1495	4.00	24.00	30	
		450 x 300 x 1495	4.00	24.00	19	
		300 x 300 x 1495	34.00	24.00	110	
	Slab	28500 x 25600 x 125	1.00	24.00	2189	
	Concrete Wall	1495 x 43600 x 250	1.00	24.00	391	
	Finishes	28500 x 25600	1.00	2.40	1751	5502

Table C4 : Approximate calculation of imposed load on the test buildings

Storey	Area (m^2)	Load (kN/m^2)	Weight (kN)	Total (kN)
Roof	729.6	2	1460	1460
Storey 9	729.6	2	1526	1526
Storey 8	762.68	2	1526	1526
Storey 7	762.68	2	1526	1526
Storey 4-6	762.68	2	1526	4578
Storey 3	762.68	2	1526	1526
Storey 2	762.68	2	1526	1526
Storey 1	762.68	2	1526	1526
	Total Imposed Load (kN)			15,194

Table C5 : Fundamental period of vibration obtained from modal analysis

Mode	Fundamental period (T_1)
Translation in X-dir	3.05 (s)
Translation in Y-dir	1.01 (s)

C2. Basic calculations according to EN 1998-1:2004

C2.1 Structural regularity

C2.1.1 Criteria for regularity in plan

EN 1998-1: 2004

Clause 4.2.3.2 **Criteria for regularity in plan**

- *With respect to lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.*

  The building is approximately symmetrical in plan with respect to the lateral stiffness and the mass distribution in both X and Y directions.

- *The plan configuration shall be compact*.

  The rectangular plan shape of the building fulfills the criteria of compact plan configuration.

- *The in-plan stiffness of the building shall be sufficiently large in comparison with the lateral stiffness of the vertical structural elements*

  The in-situ concrete floor slab of thickness 125mmconnected to the lateral load resisting system proves that the lateral stiffness of the building is large in comparison with the vertical stiffness of the test building.

- *The slenderness of the building ($\lambda = L_{max}/L_{min}$) shall not be higher than 4.0.*

  The slenderness of the building amounts to λ = 1.61 (41.3/25.6m) which can be considered as satisfied.

- *The structural eccentricity*

$e_{0x} \leq 0.30 r_x$

$e_{0y} \leq 0.30 r_y$

Refer Table C6

- *The torsional radius shall be larger than the radius of the gyration of the floor mass in plan*

$r_x \geq l_x$

$r_y \geq l_y$

According to Table C6, the selected building does not fulfill this requirement. The building was considered as torsionally fleixible

Table C6 :Structural eccentricity, torsional radius and radii of gyration in each horizontal direction

Level	Direction X				Direction Y			
	$e_{o,x}$	$0.3r_x$	r_x	l_s	$e_{o,y}$	$0.3r_y$	r_y	l_s
Roof	0.365	3.2948	10.9826	14.03	0.3146	8.7865	29.2882	14.03
Storey 9	0.3519	3.2876	10.9585	14.03	0.3146	9.2198	30.7326	14.03
Storey 8	0.3391	3.2785	10.9283	14.03	0.3135	9.6897	32.2989	14.03
Storey 7	0.3268	3.2691	10.8969	14.03	0.3119	10.2332	34.1106	14.03
Storey 6	0.3149	3.2571	10.8569	14.03	0.3093	10.9355	36.4518	14.03
Storey 5	0.3033	3.2458	10.8192	14.03	0.3072	11.8557	39.5191	14.03
Storey 4	0.292	3.2319	10.773	14.03	0.3046	13.1144	43.7145	14.03
Storey 3	0.2798	3.2191	10.7304	14.03	0.3045	14.9894	49.9648	14.03
Storey 2	0.2665	3.2006	10.6685	14.03	0.3061	18.1378	60.4592	14.03
Storey 1	0.2545	3.1743	10.581	14.03	0.2909	24.1001	80.3335	14.03

C2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration

Structural eccentricities and torsional radii have been calculated using the same method as described in A2.1.1.1 under the building A. The results are tabulated as below.

Table C7 : Structural eccentricity in each horizontal direction

Level	$F_{ix}=F_{iy}=M_i$	$R_{z,i}(F_x)$	$R_{z,i}(F_y)$	$R_{z,i}(M_i)$	$e_{o,y}$	$e_{o,x}$
Roof	10^6	0.0916	0.1063	0.2912	0.3146	0.365
Storey 9	10^6	0.0817	0.0914	0.2597	0.3146	0.3519
Storey 8	10^6	0.0713	0.0771	0.2274	0.3135	0.3391
Storey 7	10^6	0.0606	0.0635	0.1943	0.3119	0.3268
Storey 6	10^6	0.0498	0.0507	0.1610	0.3093	0.3149
Storey 5	10^6	0.0392	0.0387	0.1276	0.3072	0.3033
Storey 4	10^6	0.029	0.0278	0.0952	0.3046	0.292
Storey 3	10^6	0.0197	0.0181	0.0647	0.3045	0.2798
Storey 2	10^6	0.0116	0.0101	0.0379	0.3061	0.2665
Storey 1	10^6	0.0048	0.0042	0.0165	0.2909	0.2545

Table C8 : Torsional radii in each horizontal direction

Level	$F_{ix}=F_{iy}=M_i$	$U_{x,i}$	$U_{y,i}$	$R_{z,i}(M_i)$	r_x	r_y
Roof	10^6	249.7916	35.1237	0.2912	10.9826	29.2882
Storey 9	10^6	245.2849	31.1870	0.2597	10.9585	30.7326
Storey 8	10^6	237.2274	27.1578	0.2274	10.9283	32.2989
Storey 7	10^6	226.075	23.0716	0.1943	10.8969	34.1106
Storey 6	10^6	213.9256	18.9773	0.1610	10.8569	36.4518
Storey 5	10^6	199.2801	14.9361	0.1276	10.8192	39.5191
Storey 4	10^6	181.923	11.0487	0.0952	10.773	43.7145
Storey 3	10^6	161.5221	7.4497	0.0647	10.7304	49.9648
Storey 2	10^6	138.5365	4.3137	0.0379	10.6685	60.4592
Storey 1	10^6	106.4824	1.8473	0.0165	10.581	80.3335

Table C9 : Radius of gyration

Level	l (m)	b (m)	l_s
Roof	41.3	25.6	14.03
Storey 9	41.3	25.6	14.03
Storey 8	41.3	25.6	14.03
Storey 7	41.3	25.6	14.03
Storey 6	41.3	25.6	14.03
Storey 5	41.3	25.6	14.03
Storey 4	41.3	25.6	14.03
Storey 3	41.3	25.6	14.03
Storey 2	41.3	25.6	14.03
Storey 1	41.3	25.6	14.03

C2.1.2 Criteria for regularity in elevation

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Clause 4.2.3.3

In this building, all the lateral load resisting system run without interruption from foundation to the top. Also both the lateral stiffness and the mass of the individual storeys remain constant or reduced gradually. Further, the ratio of the actual storey resistance to the resistance required by the analysis do not vary disproportionately between adjacent storeys. Since these requirements have been fulfilled in the case of investigated building, the building was considered as regular in elevation.

Overall, the building was considered as torsionally fleixible.