Impact of friction dampers and ductility factor on the seismic response of concrete moment resisting frame buildings

Anne-Gaëlle Pilorgé

A Thesis

In

The Department

Of

Building, Civil & Environmental Engineering (BCEE)

Presented in Partial Fulfillment of the Requirements

For the Degree of Master of Applied Science (Civil Engineering) at

Concordia University

Montreal, Quebec, Canada

November 2018

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Anne-Gaëlle Pilorgé

Entitled: The impact of friction dampers and ductility factor on the seismic response of concrete moment resisting frame buildings

And submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Civil Engineering)

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

Dr. K.Gala Chair
Chair's name

Dr. A. Youssef Examiner
Examiner's name

Dr. L. Tirca Examiner
Examiner's name

Dr. A. Bagchi Supervisor
Supervisor's name

Approved by Dr. A. Bagchi
Chair of Department or Graduate Program Director

November 26, 2018

ABSTRACT

Infrastructures around the world are impacted by seismic events and therefore can suffer different types of losses that include life, structure, economy and much more. It is important to control the vibration in structures using appropriate design methods, materials, and energy dissipation devices. There are many different types of energy dissipating devices providing supplemental damping to structures and control their vibration response. This research focuses on friction devices, particularly, the inline friction dampers used in diagonal bracings to control the vibration in buildings. There is no standard design process available in the National Building Code of Canada to design buildings with friction dampers. The procedure suggested in FEMA guidelines is quite complicated to use. The focus here is to use a rational method for building design with friction dampers and demonstrate the impact of friction dampers in the design process, and seismic response. Currently, dampers are used as a device, which are supplementary to the structure post- design, to increase its strength and stiffness that benefit structures. However, that produces a highly conservative design which may not be economically justified. By letting the dampers take about a tart of the lateral forces, structure can be optimized. The effect of fiction dampers was observed by the reduction of moment and shear on columns, the reduction of cost. Six structures were designed for this study: elastic with and without dampers, moderately-ductile with and without dampers and ductile with and without dampers.

This study demonstrates that by designing and applying friction dampers into the design stage, the beams and columns attract less moment and shear affecting their sizes. While designing the structure, adding dampers helped reduce the cost in material for all three structures by around 7.5% in contrasts to the same model without dampers. An optimization of the structure section was made after adding the dampers into the structure. The impact of moment and shear into the columns and beams was shown to also be reduced of nearly 25-40% (the average is 29.5%). The seismic response of the different building models was determined using nonlinear pushover and time-history analyses. The results show that despite

having smaller sections for beams and columns, the structures with dampers have reduced drift as compared to those without dampers. It was clearly demonstrated that friction dampers have an impact into the design of structures making them stronger with a higher response and lower cost. After calculating the cost of material and the overall results of analysis, the ductile structure is found to be the most economical choice. However, considering the post-earthquake damage and repair cost, the moderately-ductile structure with dampers will be a better option.

ACKNOWLEDGEMENTS

I would first like to thank my thesis advisor Dr. Ashutosh Bagchi, Professor and Chair of the Department of Building, Civil and Environmental Engineering at Concordia University. His patience and assistance were considerable, and he helped me to significantly improve my own research skills.

I would also like to thank the experts who were involved in this research project: Oscar Galindo and Richard Frazao from Quaketek Inc. Without their involvement and input, the research would not have been successfully conducted.

Special thanks to my colleagues and Jade Rabin, for helping me with the writing process and manage to always extend my motivation by encouraging me.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Table of contents

List of figures

List of tables

Chapter 1 Introduction

1.1 Background

While designing a structure, the earthquake ground motion or wind load has to be taken into consideration because they are among the strongest natural forces that can have an impact on it. The structure can respond differently to earthquake effects depending on much different design attribute (FEMA, 2016). Earthquake effects also depend on many external factors such as geographical location, soils types, and so forth. Those impacts can vary from non-harming damages to minor damages that can even result in the complete destruction of the structure over time.

Vibration is common in many structures used in mechanical, civil and aerospace engineering applications. The amplitude of vibration in a structure lessens over time as the energy get dissipated due to damping. Many different approaches, such as the supplemental damping devices and vibration energy dissipaters can be used to minimize the impact of seismic vibrations on structures. However, it has been demonstrated that these techniques lose efficiency over time [7]. Structures with a high seismic vulnerability have to be carefully monitored and maintained carefully. Structural Health Monitoring (SHM) techniques were developed to help a structure's maintenance, detection of damage, and assessment of its condition over time. Expenses related to health monitoring are expected to be avoided for new structures by developing advanced technologies that with time will not degrade. It will be expected to dissipate energy developed by seismic vibrations and control structural deformations. Many types of technologies exist for vibration suppression in buildings, which include different types of dampers and based isolators. Friction damper is in the market for several decades and Pall Friction damper [22] is one of the widely used one. While friction dampers are cost effective and easy to use, there are not enough studies on their durability behavior and design effectiveness, and the life cycle cost or resilience of buildings utilizing them.

1.2 Seismic impacts on buildings

Earthquake ground motion can affect a structure and how it reacts in various ways and levels. One of the hardest and most challenging parts of designing a structure is taking into consideration and understanding the earthquake ground motion effects. A structure may be exposed to forces that are way stronger than those assumed in the design. Ground motion impacts a structure on various attributes like the materials, structural elements, and design approaches. More precisely, for example, it can influence some design parameters like ductility or stiffness.

While designing a building, two main design characteristic elements have to be taken into consideration. The two principal characteristics correspond to the significant impact on the strength and structural resistance of each structural element. They are the strength and stiffness of the elements and the overall structure.

Stiffness is different from the actual structural members' design strength but will impact the resistance and strength of the structure. Certain members will have to be redesigned even though they have the necessary strength, but the deformation is excessive, and the stiffness needs to be increased. A basic equation of stiffness can be expressed as:

$$\kappa = \frac{F}{\delta} \tag{1.1}$$

The stiffness is obtained by the force applied to the structures, F, divided by the resulting displacement, δ [7].

During the design process, the relevant design code and standards are used to satisfy the minimum strength and deflections limit requirement. Stiffness also has a high impact on damper design, which will be discussed in more details later.

In structural design, deflection limits are also determinate by the drift limits that can be found in NBCC 2015 division B part 4.1.8.13 [18].

Ductility of a structure or a structural member can be defined as post-yielding displacement ratio. Three main ductility designs are considered in the Canadian code: elastic, moderately ductile, and ductile.

When a structure is subjected to ground motion, it is pushed back and forward. When the intensity of ground motion is high, the structure may reach the peak level of displacements where permanent deformation occurs, risking structural damages. This deformation is an impact of earthquake ground motion, in its way of dissipating the induced energy.

The more ductile the structure is, lower the force it can take before permanent deformation, but dissipates a significant amount of energy through inelastic deformation before failure. However, the ductility of a building also lends the structure to damages, which may be costly to repair.

Depending on the level of ductility used during the design process of a structure, some special provision is required and indicated in the CSA 4th edition chapter 21 [3].

The structure is designed in a way that when they are subjected to force higher than what they can absorb and resist (like ground motion), permanent damages could occur, but the structure should not collapse and thus be “life-safe”.

The economic impact of seismic design provisions and ductility on a building are correlated. Seismic design provision for the structural design has an economic impact; it can require the structure to be designed for larger forces. Larger forces, like ground motion, will require the design to have more significant resistance. The structural resistance is determined by strength, stiffness, and ductility. Therefore, more structural materials will be needed; more design work will be required. For example, to determinate the most optimized structure with the following conditions.

When a structure is in the presence of ground motion or vibration, structural health monitoring is beneficial and recommended because even minor damages that cannot be observed from an external view can still weaken the overall structure over-time [27].

1.2.1 Performance-based design

For many years, engineers were designing buildings considering the strength of the materials as the basis for design structure. Code limitation was the main characteristic for designing the new structure without actually knowing how the building will react under certain circumstances. However, in the early 1990s, a new, rather characteristic method was developed to determine resilience capacity. This method helps designers to have a more accurate observation of the real efficiency of buildings resisting specific criteria without always having to meet the official criteria that are required by design codes. Performance-based design helps to observe the real performance of a structure under certain conditions and can determine some specific weak points. It gives a realistic approach of a structure's action under particular loading or hazard. Performance-based design is a method to put the structure in real base action to determine the resulting deformation. This method can be demonstrated through many different methods like real-life testing or even analytical simulation. It can also target the economic aspect of a structure design by analyzing the building response; it will be able to make an approximation of both the life cost maintenance and the actual structure's cost. To make sure it gets the most economically efficient structural design.

Pushover analysis became an essential tool of performance-based design by giving an adequate analysis of the real behavior of a building under seismic stress. Time history analysis is also an adequate method giving even better result using the non-linear property of the structure; it is also a dynamic analysis. The FEMA code gives an approach on how to perform a basic performance design analysis [21, 19].

Over the last two decades, many studies have been conducted or are being conducted in this direction. Damping effect on a structure is still a significant issue on the seismic behavior. These studies are quite important in improving the life and design of structures subjected to seismic loads. They began to develop ways to deal with the damping effect in the context of structural dynamics. Many recent designs have taken into consideration of those new concepts and applied them, such that it improves the performance of the structure.

While the natural damping in a structure helps reducing the amplitude of vibration in a structure, it is often beneficial to add supplemental damping using energy dissipating devices or dampers. The main idea will be that those devices would be able to dissipate the energy that impacts the structure as a consequence of vibration. One of the technologies that has been established to increase the overall strength and longevity of the structures was designed to dissipate the vibrations applied to the structure due to earthquake ground motion, this technology is called dampers.

1.3 Dampers

1.3.1 History and development

As mentioned previously, earthquake ground motion has a significant impact on the structural design due to their strong and high load. Structures subjected to a large amount of vibration must be able to dissipate this excess energy, so it can prevent permanent deformation. The design of a structure without the use of the external energy dissipation device, entails a stronger and more rigid element so that it is safe, non-life threatening. It will also follow the conditions imposed by the requirement of the code. One of the easiest ways to get a structure to be stiffer or/and stronger is too merely to increase the size of the sections or reinforcements. However, it is an inefficient method as it brings an increased cost in labor, equipment and loss in space.

Some dampers like Tuned Mass Dampers, Tuned Liquid Column Dampers or Tuned Slosh Dampers adds extra weight to a structure [11]. It was commonly used in tall buildings to be able to control the energy dissipation. Those dampers are passive dampers meaning that they do not use any source of power and work by the impact of a structure's dynamic motion. Nevertheless, these dampers include an increase in the weight of the building, therefore a lack of space and an increase in the materials used. It also needs periodic monitoring. The premise of those dampers is that by adding weight, it will alter the dynamic characteristics, so it can have better control of damping into the structure. The application of those dampers offers an excellent way to dissipate the energy but aren't economically efficient.

These dampers can also be designed as active dampers which need the control system (software) and external power. The maintenance and the cost of that can be much higher than the passive dampers mentioned above. Many other different types of dampers were developed with time, like semi-active dampers, or hybrid dampers. The main idea of those dampers is to be able to dissipate the energy and prevent any damage related due to earthquakes.

There are many applications of various types of dampers in real structures to test their effect on structures. For example, in Tokyo, Japan a research was conducted on U-shaped steel dampers. Those dampers are already profoundly implanted in Japan since the 1995 Kobe earthquake. Those dampers had a significant impact on structures because since the device was applied to buildings, even larger-scale earthquakes had produced lower damage to them. The testing was made to determine the influence of the temperature and effect of different loading cycle on those dampers by using the hysteretic behavior as the primary comparison. It was proven that the increase in loading cycle and change in temperature has a minimum influence on a structure [13].

A viscous Damper is an energy-dissipated device that is mostly composed of a cylinder that contents viscous fluid and piston that pushes the fluid through an orifice to a separate chamber. Usually, it works as the steel piston: when it is pushed, oil runs through it and the pressure difference created will provide energy dissipation. Viscous dampers should add a range of 15-25% of additional damping to the structure to have an active effect on the structure design [28]. It is also a passive damper that doesn't need an external power to function.

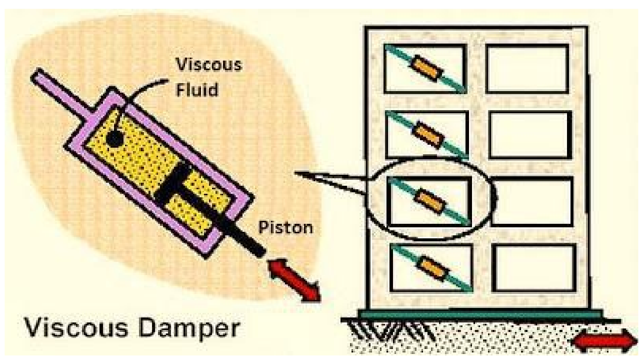


Figure 1-1 viscous damper utilizes the forced movement of fluid within damper [28]

Many researches have been conducted on the behavior of steel MRF building using the retrofit method of adding viscous dampers. It was shown that it could be used as a supplemental dissipation device. However, when the dampers are not distributed homogenously into the frame or floors, it is hard to predict how they will respond. Some approximation of a detailed expression (mathematic formula) was developed [15].

A comparison of Braced Steel Frame, Moment resistant frame and shear wall was made to be able to determine the effect of seismic damaged on them. Friction dampers were tested by using a shaking table; and it was demonstrated that no damage occurred while tested. The cost of those dampers can be considered as almost negligible expense in comparison of money saved that occurred during and after the design process. The gain of space is also a good argument, by saving space, material, future cost related to monitoring and extends his lifetime; the device is a great achievement to the development of a self-sufficient structure. An economical option: material saving, fewer and cheaper dampers. Therefore, more spaces are available with an initial cost that is reduced. Maintenance cost will also be significantly lower. For example, while designing Concordia university library, Montréal, QC, Canada. Friction damper has been chosen to replace a few shear walls. It was a good investment because it made the structure strong and increased available space and reduced material expense. The use of a bracing system, including dampers, had a benefice of saving around 6.5% of the total structural cost.

1.3.1 Friction Dampers

Friction dampers are one type of dampers that dissipates energy by overcoming friction. They are considered like one of the cheapest and simplest dampers as they use the concept of friction between two surfaces to dissipate the energy. The idea developed by Pall [22] first introduced pall friction dampers. It was introduced in 1979 and used the concept of dampers that dissipated energy by two surfaces sliding to each other, after research on the most efficient material and technique used. He was able to determinate that it was possible to have a significant rectangular hysteresis loop stable by using brake lining pads that will be in contact with another surface connected by post-tensioned bolts [22]. Since the idea and first friction dampers were developed by Pall, friction dampers have been evaluated in different directions, and different type using diverse materials or design exist, however, they all used the same concept: dissipating energy through friction as a hysteretic device. When the two pads interact with each other during a seismic excitation, the dissipation of energy is created by friction that happens when both pads slide against each other. FEMA 356 [7] introduced the first North American Guideline introducing the design of friction dampers into structural earthquake engineering in 2000 [9]. Friction dampers are often designed and included as an element in a tension/compression brace. Their cost, installation, and maintenance feed are insignificant in comparison to other design/construction cost, and they do not change the fundamental structure properties [24]. In the figure 1-2, an example of friction dampers connected to braces in Concordia University Library in Montreal.

Figure 1-2 Pall Friction dampers installed in the Webster Library of Concordia University, Montreal, Canada.

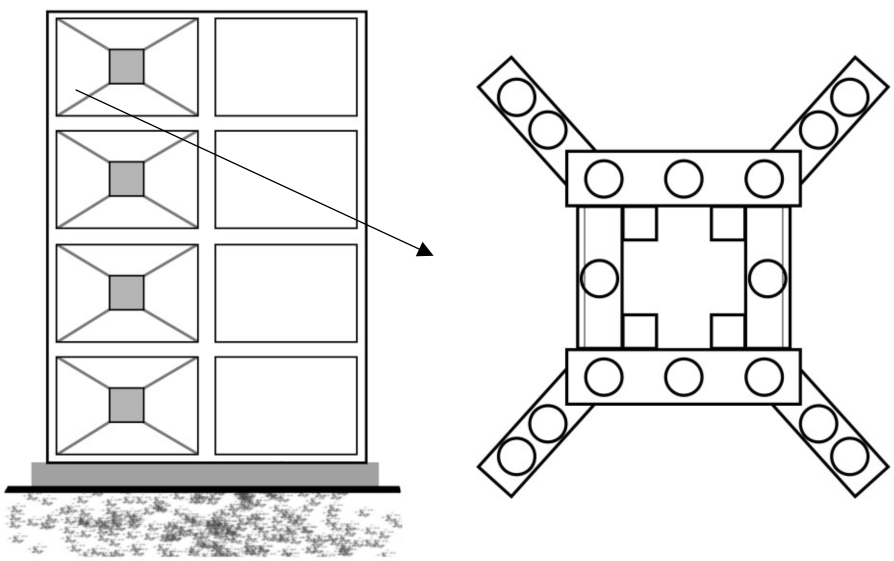


Figure 1-3 friction dampers installed in X braces in a structure

1.4 Statement of the problem

There is limited volume of research conducted on friction dampers in buildings. However, it was mostly concentrated in the steel structures. The lack of information on the influence of the inclusion of friction dampers in a concrete structure is not well explored. Friction dampers have proven to be an effective way to protect the structure against permanent deformations, failures, under the effect of ground motion. In this research, the goal will be to conduct a numerical analysis of concrete MRF structure depending on their ductility subjected to ground motion. By doing this numerical research, it is expected to make an economic assessment of including friction dampers as an integral element during the design stages of a structure.

1.5 Objectives of the thesis

The objective of this thesis is to develop a process to include friction dampers in the main stage of designing of a structure instead of adding them afterward. It will be assumed that by adding them as an element of design it can be used as both an optimizing tool for different aspects of a design and a dissipation device. The goals will be achieved by determining the efficiency of the use of dampers in MRF concrete structure through the economic aspect and its response. The work is divided in to the following three main stages,

(a) To perform an economic comparison of buildings with and without Friction dampers,
(b) To evaluate the static response of buildings with and without Friction dampers and finally
(c) To compare the seismic performance-based design on those building.

1.6 Organization of the thesis

This thesis contains three main chapters, and a discussion on the analytic research and how they obtained, through studies of different cases, scenarios and research.

The literature review and the introduction of the project and issue were stated in this chapter.

Chapter 2, the methodology. This will be a description of the steps and method used to design models used during this research.

Chapter 3, will be the analysis of the static analysis.

Chapter 4, will be the performance base design analysis including push-over analysis and time history analysis.

Chapter 5, will be the conclusion and the final assessment of final results.

Chapter 2 Methodology

2.1 Introduction

This chapter contains the description of experimental buildings design using Moment resistant frame (MRF) and its different scenarios. Those cases where defined by taking into consideration different attributes: the ductility of a similar building and the presence or absence of dampers. Material properties, reinforcement detailing, section design, drift, predicted forces on the design and analysis of specifics elements like dampers would be described in this chapter. The process started by designing a base model: a 14 stories moderately ductile building using MRF. In this study, many different scenarios where used to get an accurate comparison sample. Only the most optimize final models will be introduced and used for the research. The design process was done using the software design tool ETABS.

The seismic behavior of a structure with friction dampers was studied in this research. As discussed in the literature review many researches have been conducted on steel MRF structures and the influence of friction dampers to their seismic response. However, there is a lack of research in concrete structure, including friction dampers into the design stage. Design process for MRF steel buildings with friction dampers is more well established and many journal papers and research can be found about it. In the present days, MRF structure aren't always the most economic and best choices as a design option; however, to as a starting point in the present research, it was decided to use concrete structures with only MRF frames for research and introduction of this subject in engineering practice.

At first, 3D models were used to analyses six different cases. Those six models have a similar common core building, but they differ slightly in section seizes for beams and columns and the reinforcement ratios; and the analysis was conducted using static analysis procedure.

Static analysis is efficient to be used to get a force based analysis of the structure. With this analysis, it was possible to get accurate results of the structure's sections and reinforcements. It was designed to achieve some actual information on the effect of friction dampers on Concrete MRF structure. The influence on the moments and shear forces was computed and compared. Also, the structure was analyzed to determine its behavior to lateral loads, and how it influences the section details of the structural members and reinforcements. Different ductility levels were considered in designing the building to determine which ductility level is the most efficient with the use of friction dampers. The capacity and positions of the friction dampers are important in corralling the seismic demand. A cost analysis was also done for all six cases to determine the financial implication of each design scenario. A cost comparison between the models of the building with and without friction dampers was conducted. This analysis is also essential since the cost is a significant influencer and player in the engineering field.

A total of six different models were designed using the seismic provisions of NBCC 2015 and Canadian Standard, CSA A23.3-14. [17, 3]. Afterwards, to evaluate the seismic responses, 2D's analysis was performed using ETABS.

2D models were constructed in ETABS which had the same building properties as the 3D model. The 2D models have the same weight, story displacement and period as their 3D counterparts. The dynamics analysis was performed using 2D model as it is faster than 3D analysis, to compare two main scenarios and their ductility levels. Dynamic analysis permits to gives more precise and accurate results as the real behavior and action of a structure. Performance based design analysis will permit to observe the displacement of a structure. Frames with friction dampers and without dampers were designed in three different cases of ductility: ductile, moderately ductile, and elastic. A total of six frames were finalized and designed.

2.2 Common core Model (3D)

The base models are 3D models used for the design and static analysis; six models were made. All six models have a basic common core that will be described in this section. The structure is a 14-story high building. All floors are of 3.5 m height except for the ground floor with a height of 4.5 m. The building has a length in both direction of 40 m, with five clear spans of 8 meter each. Columns on each floor are divided into 3 different groups: 4 corners columns, 16 external columns, and 16 internal columns. Beam on each floor was designed in 2 different groups: 20 external beams, and 40 internals beams. The slabs thickness was taken as 200 mm [18].

Figure 2-1 & 2-2, represent the different columns and beams categories. However, when dampers are present into the design internal columns and beams are divided into two sub-categories: beam and columns connected to the dampers and the other internal beam and columns.

The reason for this sub-category is because of the difference in the moment, axial and shear force caused by the damper and its own weight.

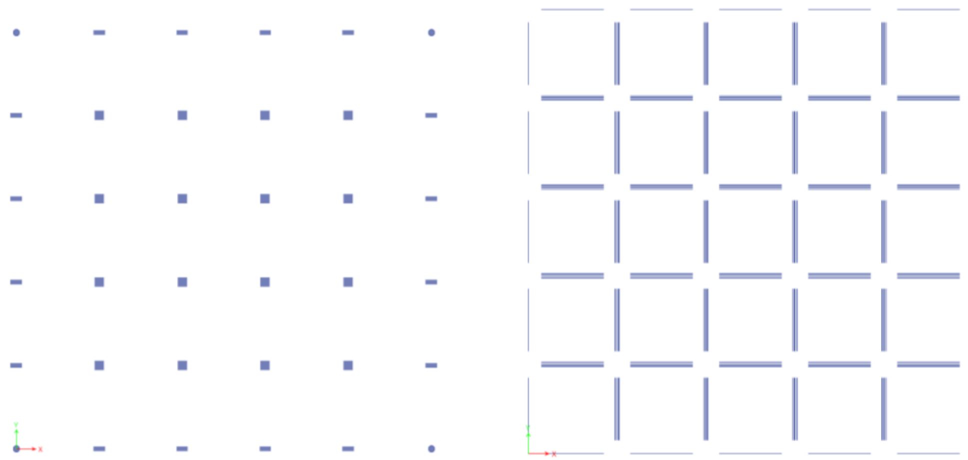
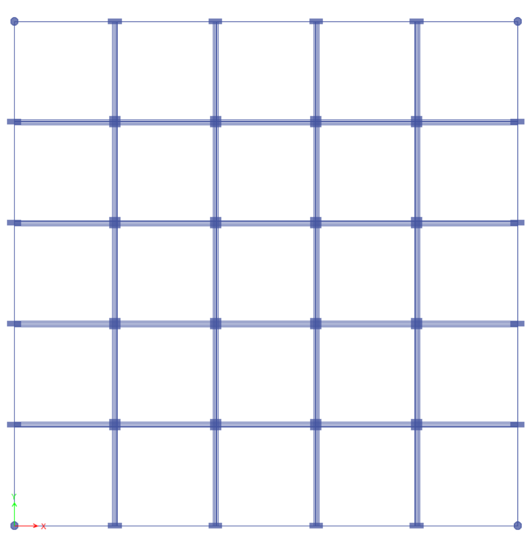


Figure 2-1 (1) Columns categories color coded & (2) beam categories color coded for each floor

Legends:

Square: Internal Columns



Rectangular: External Columns

Circle: Corner Columns

Thick line: Internal Beams

Single line: External Beams

Figure 2-2 columns and beam color-coded categories

The building can be considered a ‘regular structure’ and be designed using similar static equivalent force procedure (NBCC 4.1.8.7). The structure has a high of 50 m < 60 m and have a $T_a < 2.00$ sec in both directions. $0.075*h_n^{3/4}=0.075*(50)^{3/4}=1.41$

(NBCC 4.1.8.11.3.a.ii.) [18]. for static analysis the structure was design using a period of 2 s, when they were found to be higher 2 s.

However, in NBCC 2015, division B part 4.1.8.9. [18], the code mentioned that the height for moderately ductile structure for ¸¨$I_EF_aS_a(0.2) > 0.75$ ¨ is limited to 40 m.

In Vancouver city hall area with a site class C, $I_EF_aS_a(0.2) = 0.848 > 0.75$., which means that the models with moderately ductile ductility MRF need to be limited to a total height of 40 m. However, it was decided to ignore this condition in order to study the behaviiur of structures with and without friction dampers for different ductility and determine if a building of such height can be properly designed with dampers to achieve the other design constraints including the drift limit. No real code limitation in height exists for the specific cases of 'structures with dissipations devices'.

Table 2-1 natural period, 3D buildings

MODEL	**ELASTIC Model (EL)**	**ELASTIC Model (EL-D)**	**MODERATE-DUCTILE Model (MD)**	**MODERATE-DUCTILE Model (MD-D)**	**DUCTILE Model (DUC)**	**DUCTILE Model (DUC-D)**
DAMPERS	NO	YES	NO	YES	NO	YES
T_a (s) Design	1.48	1.32	2.37	1.96	2.63	2.21
T_a (s) used	1.48	1.32	2.00	1.96	2.00	2.00

Reduction factor slabs, beam, and columns

As mentioned in section 21.2.5.2 from Canadians concrete handbook [3], reduced section property should be applied to the moment of inertia of concerned members. It was assumed that Slabs: $I_m=0.20I_g$, Beam: $I_m=0.40I_g$ and columns: $I_m=0.70I_g$.

2.2.1 Location and data

The structure was designed for a chosen location of Vancouver, for the use of the code for the snow load, earthquake ground motion, ground data. The building was assumed to be an office building and as by code mention; the ground force will be designed using a live load of 4.8 kPa for the ground floor and floors above with 2.4 kPa (except on the top floor, snow load was used instead). The super-imposed dead load added to the building structure as an extra weight assumed for mechanical used taken as 1.5 kPa. The building has concrete MRF frames. The snow load applied to the roof was calculated using NBCC code part 4, for Vancouver Hall.

Therefore, the appropriate design snow load for the building is 1.64 kPa. Calculation is provided in the appendix A. To get accurate results, the base model was designed by two main steps. The first step was designing a model that was passing ETABS requirements and hand-calculations method was used to correlate with ETABS results. The moment, axial, torsion forces of members extracted from ETABS, was used to conduct a hand design calculation following the Canadian code. Six final building models were finalized and used for a primary analysis, and the same main specifications mentioned above were used for all of them. Those buildings were designed to investigate the influence of friction dampers on concrete MRF building [2].

2.2.2 The building specifications and ductility

When designing for ductility, some special requirements are needed, and it can be found in Chapter 21 of 2014 Canadian concrete handbook, special provision for seismic design specified some special conditions. Force reductions factors should be applied. R_dR_o, data table can be found in NBCC Chapter 4, part B. Table 4.18.9. [18].

- Model (EL) elastic: $R_d = 1.0$, $R_o = 1.0$

  No special condition for seismic performance needs it.

- Model (EL-D) elastic with dampers: $R_d = 1.0$, $R_o = 1.0$

  No special condition for seismic performance needs it.

- Model (MD) moderately ductile: R_d = 2.5, R_o = 1.4

  More details in the Canadian concrete handbook 2014: section 21.7.2

- Model (MD-D) moderately ductile with dampers: Rd =2.5, Ro = 1.4

  More details in the Canadian concrete handbook 2014: section 21.7.2

- Model (DUC) ductile: R_d = 4.0, R_o = 1.7

  More details in the Canadian concrete handbook 2014: section 21.4

- Model (DUC-D) ductile with dampers: R_d = 4.0, R_o = 1.7

  More details in the Canadian concrete handbook 2014: section 21.4

2.2.3 Damper placement

In today's practice friction dampers are normally positioned near elevator shaft or main openings. They can be positioned in external frame and have a better effect on the structure. However, due to the architectural aspect of designing structures in present day structures, they are mostly positioned in internal frames of a building. In the present study, it was decided to place the dampers in a similar manner of current practice in construction and real-life buildings. As recommended in the FEMA 356 [7] guidelines, it is required to have at least 4 dampers in each direction. In the present case study building, dampers are present on the following frames: C (2-3 &4-5), D (2-3 &4-5), 3(B-C &D-E) and 4(B-C &D-E) as shown on Figures 2-3, 2-4 and 2-5.

As mention in FEMA 356 [7] section 9.3.1, passive energy dissipations devices like friction dampers have to be at least 4 energy dissipation devices in each directions with a slip-load force of at least 130% of the maximum calculated displacement load and friction dampers are independent to each others and do not need to be continuous on every floor of a structures. It can offer more options of placement into a building.

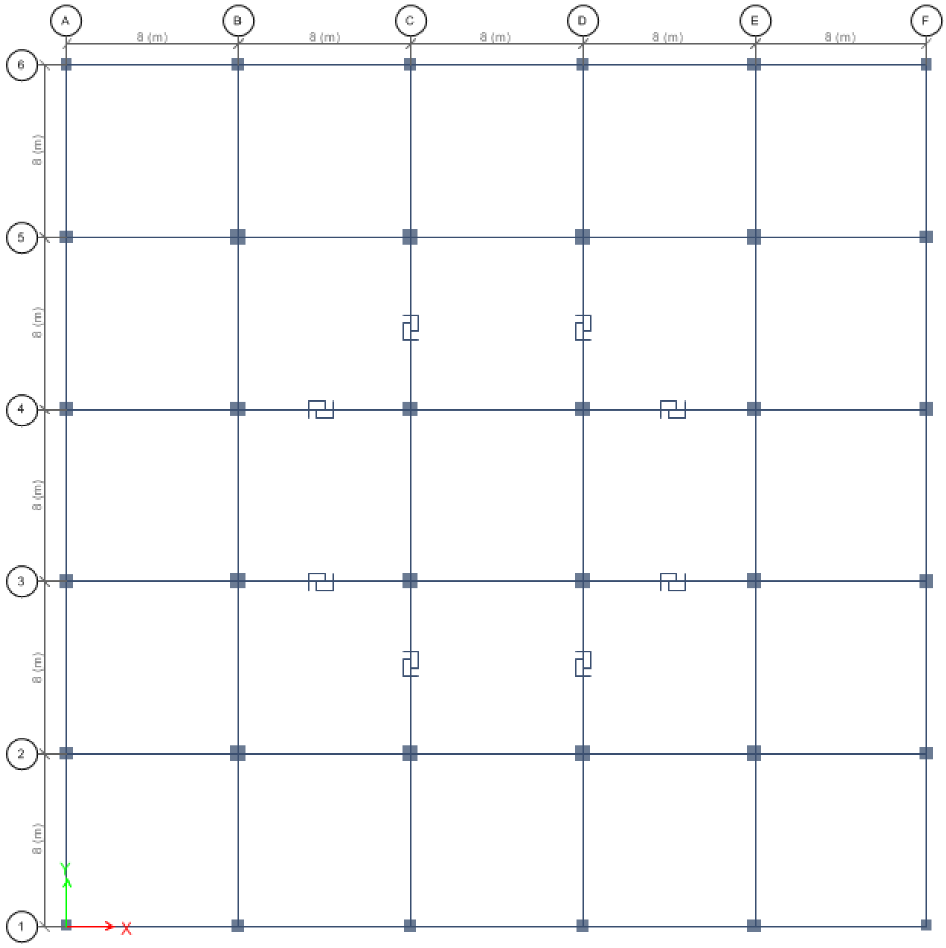


Figure 2-3 plans view with dampers

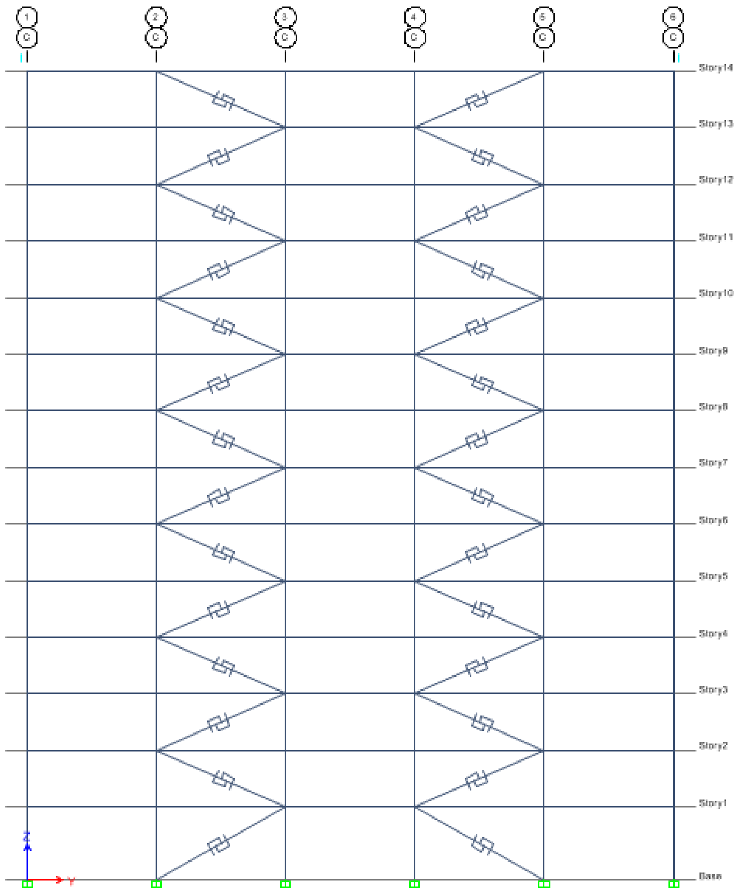


Figure 2-4 Frames views with dampers position

2.2.4 Dampers Design

Dampers were selected for each floor as shown in Figure 2.2-4. They are connected by HSS steel beam and need to be able to slip during the design earthquake motion. In Figure 2.2-6, the representation of a friction damper connected to HSS steel beam is shown. The steps used to select the dampers were provided below.

The base shear and stiffness of each floor were used and calculated for the same ductility no-dampers model. Here, between 25%-35% of the shear is assumed to be taken by dampers while proportioning the design forces, and four dampers are placed in each direction at every floor as mentioned previously [33].

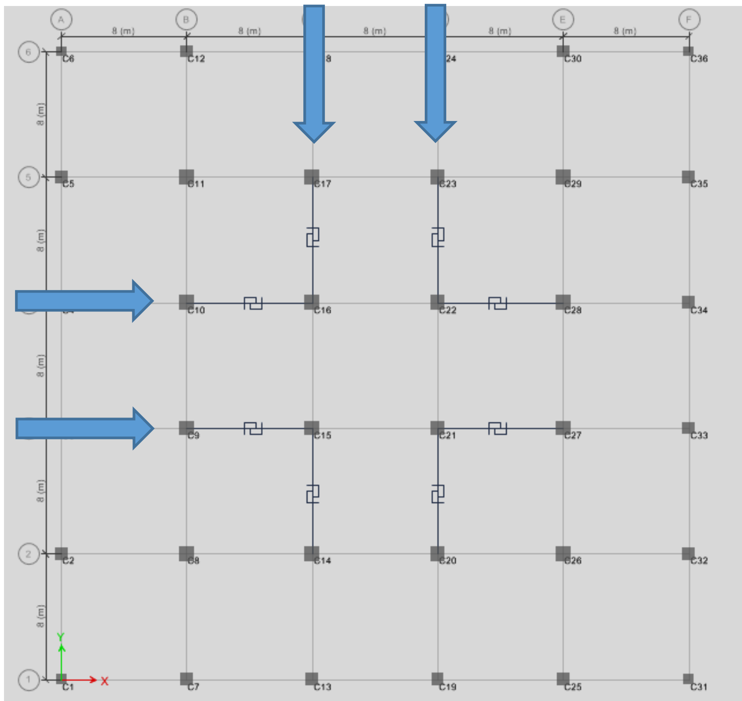


Figure 2-5 Floor view and dampers directions

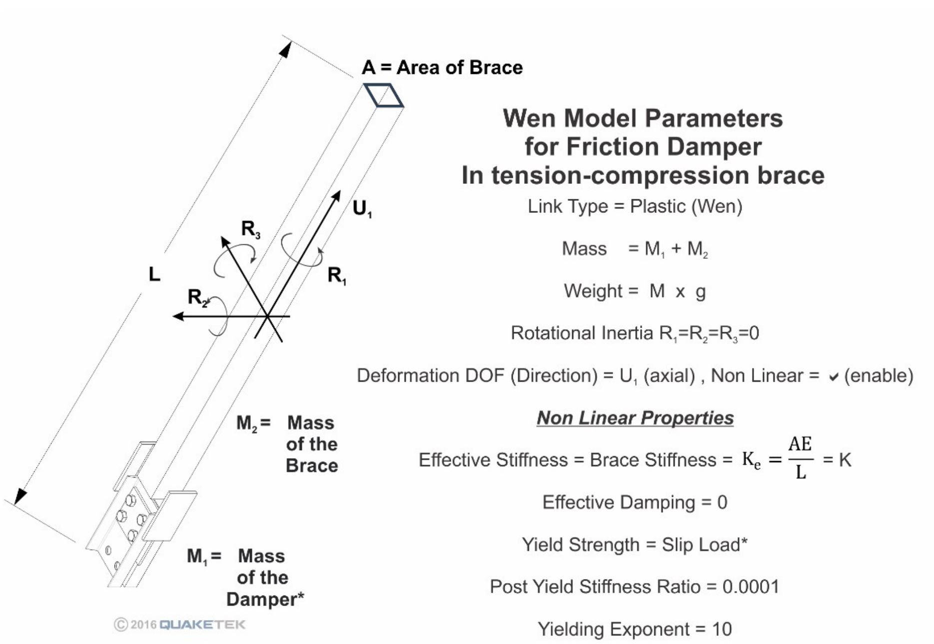


Figure 2-6 Wen Model parameters for Friction Dampers in tension-compression braces

The length of the dampers (Floors 2-14) was calculated has $l = \sqrt{{h_f}^2 + {l_s}^2}$

h_f = height of the floor = 3.5 m (Floors 2-14) and 4.5 for the ground floor.

l_s = length of the span= 8 m

The angle is also needed and calculated using this formula: $\theta = \tan^{-1}\frac{h_f}{l_s}$

Table 2-2 length and angle of links

Floors	**l**	$\boldsymbol{\theta}$
2-14	8.73 m	23.63°
Ground Floor	9.18 m	29.37°

$$\Delta_{f\&br,j} - \frac{V_{f\&br,j}}{k_{u,j}} + \frac{V_{br,j}}{k_{u,j}} = 0 \qquad (2.1)$$

$\Delta_{f\&br,\, j}$ - total shear deflection at floor j
$V_{f,\, j}$ - lateral shear force at floor *j* exerted by the unbraced frame alone

K_u=stiffness by floor

K_{br} = stiffness by 1 braces

$k_{br,\, j}$ / $(k_u+k_{br})_j$ =0.6

$Kbr,_j = k_{br,\,j} / (k_u+k_{br})_j * K_u / (1 - k_{br,\,j} / (k_u+k_{br})_j) = 0.6*K_u/0.4 = 1.5* K_u$

We have 4 braces by floor so $K_{br,\,1} = 1.5/4*K_u=0.375*K_u$

Shear by damper will be $V_{br}= V_f*0.6/2/4 = 0.075*V_f$

Damper slip force: $\frac{V_{br}}{\cos\theta}$

Braces should be verified to behave elastically in axial compression and tension under a force equal to 130% design slip-load (FEMA 356) [7].

Slip load used: 1.3* Dampers slip force: $\frac{1.3V_{br}}{\cos\theta}$

From a manufacturer's Information sheet, the weight of a damper with the right dampers slip force can be found. The design of the steel HSS braces: a brace must be selected, so it passed:

Braces deflection & slip force of the braces > slip load used

Design of the links for ETABS (dampers and braces)

The stiffness of the link will be calculated using the Area of the Braces selected: $k_{final-1links} = \frac{AE}{L}$

Total Mass of the links: $2 * M_{braces} + M_{dampers} = M_{links}$ (Kg)

Total weight of the links: $M_{links} / 9.81 = W_{links}$

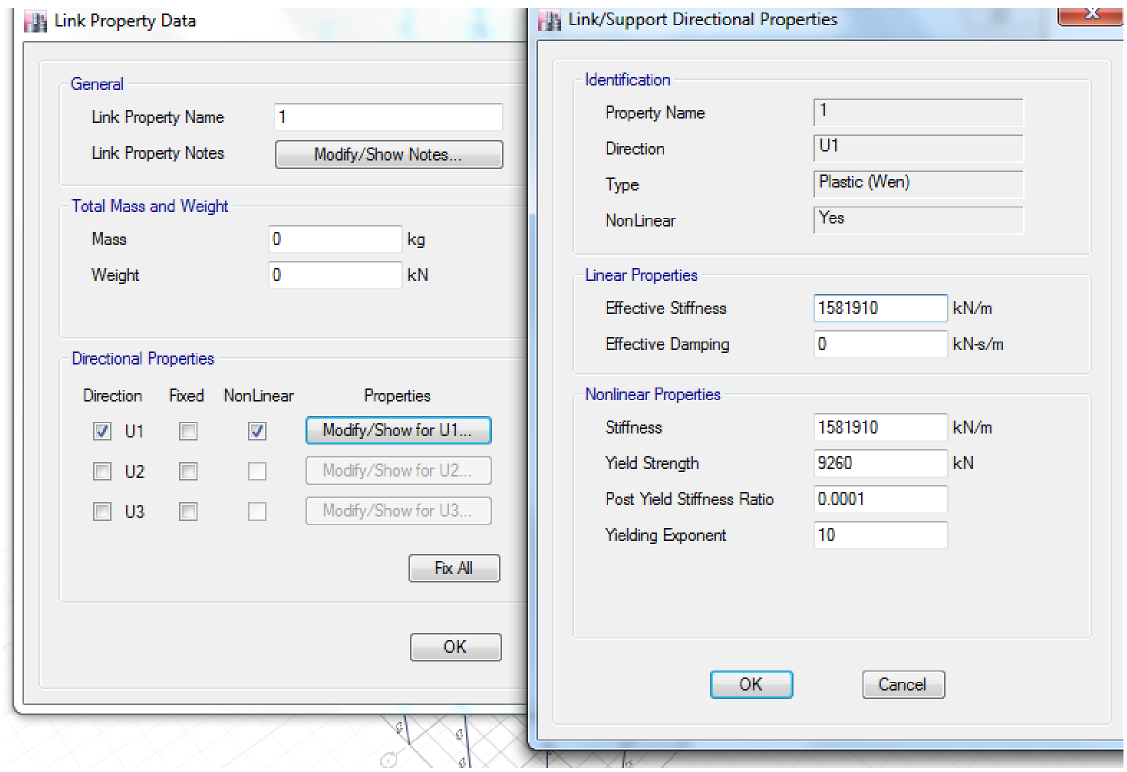


Figure 2-7 Links property in ETABS

2.3 Steps of the design

After establishing the commons cores of the building models, the design was done by following certain steps and constraints. This section contains the steps of the design that were used. All the buildings where designed using ETABS, with the specifications mentioned previously. At first, the description of the 3D models will be made by how it was designed on ETABS. After the design, it will explain how the building was analyses using static analysis. It will be followed, by the 2D models; design steps and dynamics analysis.

2.3.1 3D analysis, static analysis

The first model, the 'base model' was designed as a moderately ductile frame with force reduction factor of R_d =2.5, R_o = 1.4. Slab thickness was selected by using the deflection limits of the relevant Canadian code. The section of beams and columns were modified until we got an optimized building. As steel is more expensive than concrete, it was important for an optimized building to have columns reinforcement around 1%. The design was made to follow the strong column-weak beam design. Beams were designed to be able to pass the joins shear between columns and beam, the deflection code specification.

Hand- calculations for design were also made to select the beam and columns reinforcement and were proven to be similar to the ETABS results. Excel sheet and sample calculations can be found in the appendix A. Load applied to the model, follow the code specification.

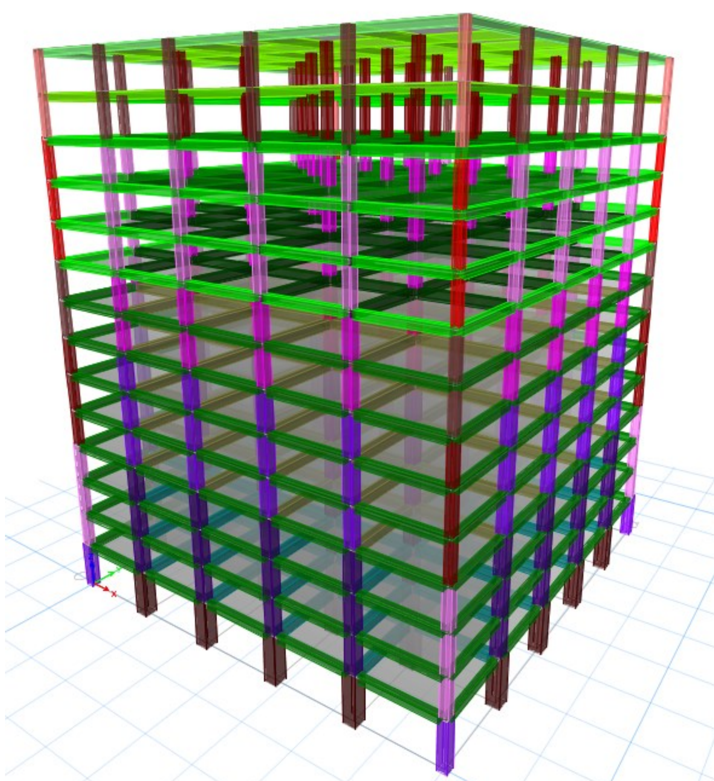


Figure 2-8 3D models view

2.3.2 Static linear Analysis

A linear analysis is conducted when the relations between the forces applied to the structure and the displacement stay linear. When designed the stress must remain in the linear elastic range of it and have a constant stiffness matrix.

A linear analysis was conducted on the three building models that does not include any dampers. At first, after having applied section size, properties of the building, an analysis of the building have been conducted.

The building was designed using load as earthquake (EL), live (L), dead (DUC), self-weight (SW) and snow (SL) loads.

The load combinations used are as followed: 1.25*(D+SW) +1.5*L

1.25*(D+SW) +1.5*SL

1*(D+SW) +0.5*L +E

1*(D+SW) +0.5*L –E

1*(D+SW) +0.5*SL +E

1*(D+SW) +0.5*SL –E

1*(D+SW) +E

1*(D+SW) –E

P-Delta effects

P-Delta effect is a secondary effect on a structure and must be taken into consideration during the design stage. His influence increase with the height and number of stories in a building and need to be carefully taken into consideration when buildings are considered ‘high rise’. On ETABS p-delta was chose to be ‘iterative based- on loads,' and loads were chosen as follow: 1*D+0.5*L+0.25*SL.

2.3.3 Static non-linear analysis

The steps for non-linear and linear analysis of static analysis is similar; however, non-linear analysis takes into consideration non-linear material properties, p-delta effects or special elements. In our case, the dampers are considered as "special elements."

A static non-linear analysis was conducted on the 3D models with dampers. The reason why non-linear static analysis was conducted is due to the fact dampers are not activated in the linear state on ETABS. Same earthquake load was applied as their similar building without dampers, this assumption is to prevent a bug on the software that occurs when design in non-linear static analysis with code design earthquake on ETABS. Earthquake was defined as user load on ETABS with identical load design on the similar non-dampers building. The same load combination and P-Delta effect were taking into consideration as the static linear analysis.

2.3.4 Economic Aspect of the Design

As a significant influencer in the research; the economic aspect of designing buildings in correlation with the economic aspect of dampers design. The first analysis that was conducted when the six-based model was designed, including the reinforcement, was a cost analysis of material in each building. A direct method was used by merely compared the amount of steel, and concrete used to each other. An assumption of the total material cost was conducted by reinforcement details, gross concrete and dampers material need it in every single building. After this calculation of material cost, a comparison between the amount of steel and concrete in the same building was conducted, note that steel material his more expensive than concrete. The cost of future expense was also taken in consideration by seeing that dampers will bring some future savings in life cost due to his impact in dissipation energy and prevent some minor to significant damage that can happen during seismic excitation. However, space-saving needs also to be taking into consideration during the economic analysis of the designs. In conclusion, the most economical building is not always the one that cost the less but also the building that his the less expensive in comparison of space available, resilience level and future maintenance cost.

2.3.2 2D analysis, Dynamics Analysis

To simplify the seismic performance analysis of the building, 2D models were developed for each different cases. A 2D model was constructed by putting in series half of the building using Frame C as the first frame. As shown in Figure 2-8, three frames were put in series and connected by rigid links. To ensure that the 2D models are equivalent to the 3D model of the building, they were modelled with the same mass, periods and deflections at each level of the buildings.

Slab stiffness is accounted in the 2D model by increasing the beam stiffness. An approximated analytical calculation using the displacement of both 3D and 2D model was used. It was able to define an equivalent model. Since half of the model was designed on series, the 2D model mass is half of the real building weight. The extra mass from the slabs and half of the beams in the other directions was added to each joints of the 2D model and was calculated by using the principle of the tributary area of every joints.

A floor of the models can be divided into 25 identical squared area, for half of the building it means 12.5 squares. A square is taken as an 8m by 8m tributary area of the full weight of 1 floor, not including the frames designed. Every floor is divided into 25 squares of 36 m^2.

-joints connected to corner columns take 25% weight of 1 square

-external columns take 50% weight of 1 square

-internal columns take 100% weight of 1 square.

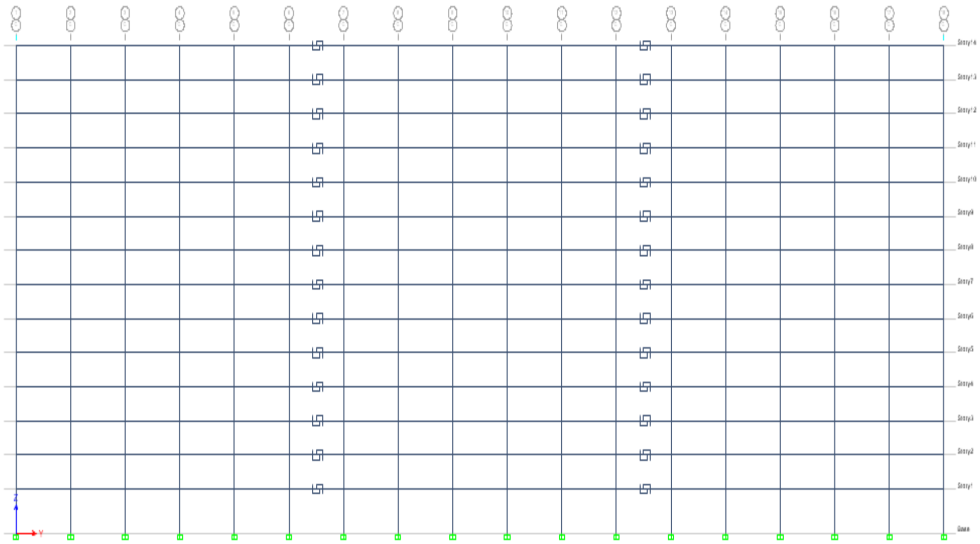


Figure 2-9 2D Frame view without dampers

The torsion Effect on the structure was taken into consideration on the 2D model following the methodology on FEMA 356 Section 3.2.2.2.2 [7]:

"The displacement multiplier, η, at each floor shall be calculated as the ratio of the maximum displacement at any point on the floor diaphragm to the average displacement (δmax/δavg). Displacements shall be calculated for the applied loads."

For the Non-linear Dynamic Procedure, the largest ratio of the structure for the maximum displacement found will be applied as a factor to the ground acceleration record used on ETABS.

Table 2-3 show the ratio used for torsion effect to amplify the 10 ground motion (GM) acceleration records for each model.

Table 2-3 Torsion effect ratio used to amplified the GM acceleration record

	EL	EL-D	MD	MD-D	DUC	DUC-D
ratio	1.67	1.51	1.67	1.53	1.67	1.45

The building models were analyzed using a fast-non-linear time history analysis (FNA). Fast non-linear time history analysis was conducted on each building, as for the building that has dampers they would be activated when the force in them exceeds the slip load. Hinges were defined in each building to get an accurate pushover analysis, using non- linear static analysis. In additions, a time-history analysis was conducted using ten different ground motions.

Six different 2D models were created with different attributes and can be described as follow: The following three models were without any dissipations devices: elastic, moderately-ductile, and ductile. Three other models were created from the above models, but with frictions dampers on each floor and direction. The seismic response analysis will be used to compare the models and give a reference idea about the effect of friction dampers on a building.

2.3.3 Non-linear time history and push-over analyses

The 2D models are used to conduct an analysis of the seismic response of the structure. It is an analysis of dynamic response of the building occurring at increase of time by applying specific ground motion to the structure. Each model has the same core parameters for analysis. A total of 10 ground motion was selected from PEER ground motion database website and was scaled according to the Vancouver city hall response spectrum [25]. Vancouver response spectrum is applied directly on ETABS by using the code of NBCC 2010, and data taken from NBCC 2010, part 4: 4.1.8.11 and table C.2 [18].

Figures 2-9 & 2-10 represent Vancouver response spectrum, applied on the structures. Figure 2-11 represent matching spectrum of the 10-ground motion with Vancouver spectrum, it can be observed that the matching spectra are higher than Vancouver spectrum. Figure 2-12 represent the average of all 10-ground motion matching with Vancouver spectrum and Vancouver spectrum.

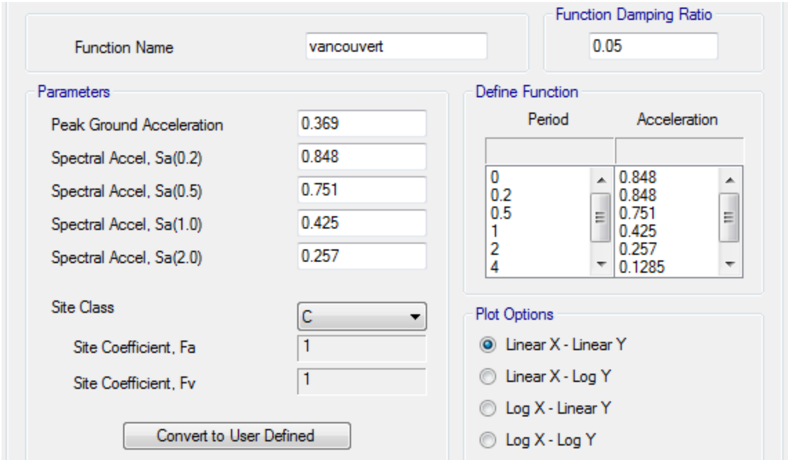


Figure 2-10 Vancouver Response Spectrum ETABS Data

Figure 2-11 Vancouver Response Spectrum curve extracted from ETABS

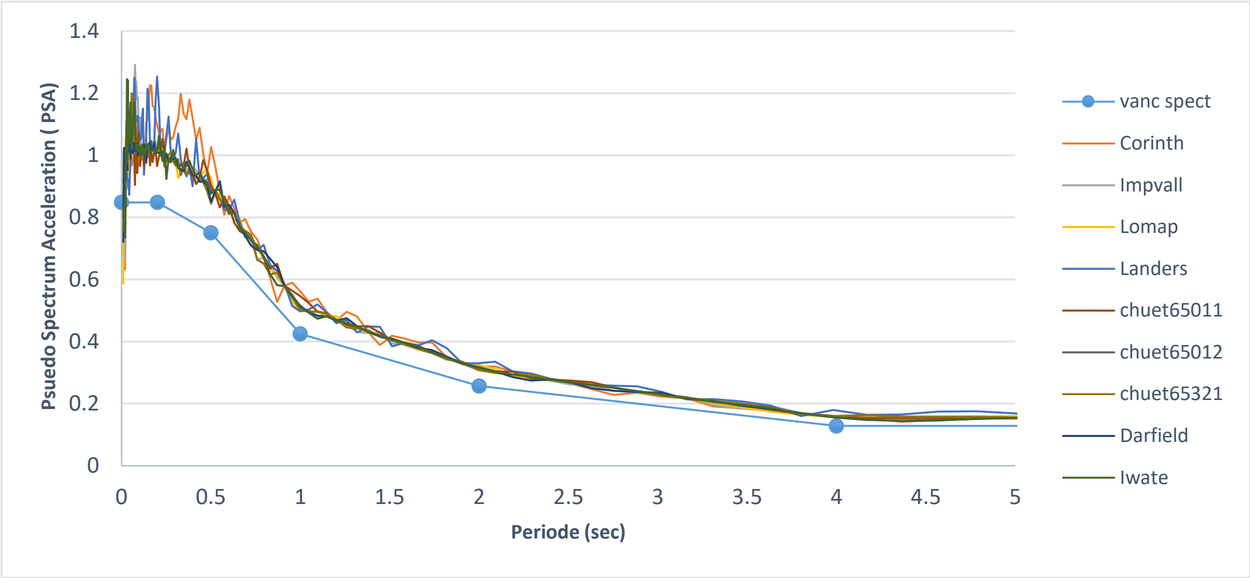


Figure 2-12 10 Ground-motion matching with Vancouver spectrum (5% damping)

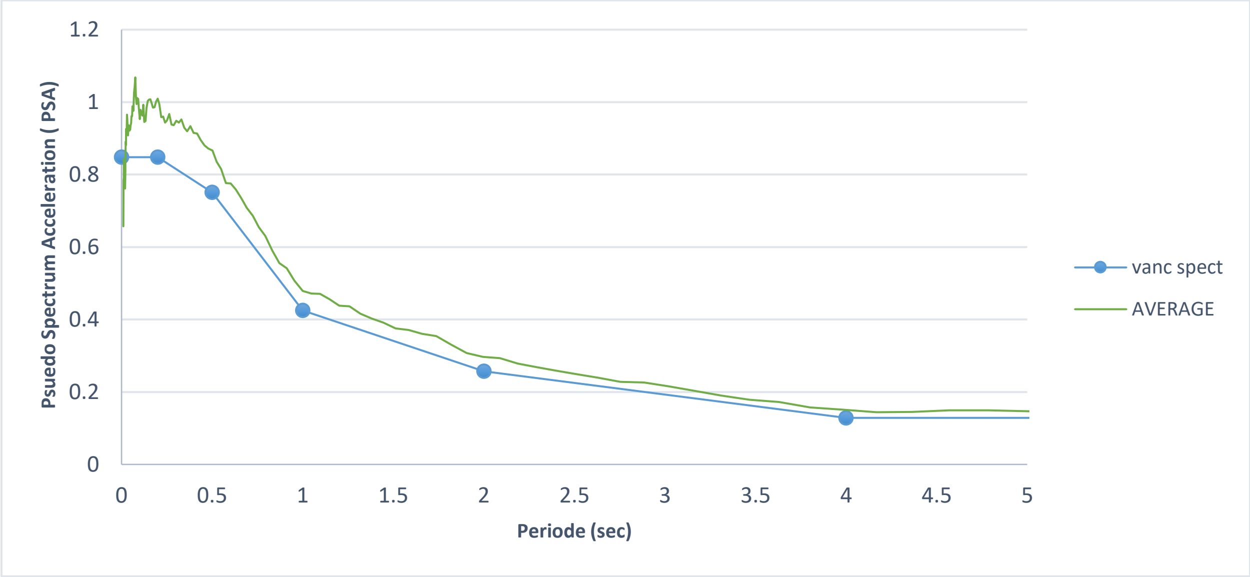


Figure 2-13 Average Ground-motion matching Vancouver Spectrum

Table 2-4 Ground-motion characteristics

	Magnitude	Peak accelerations	durations
Corinth	6.6	236.8	41.3
chuet65011	6.8	188.2	60.0
chuet65012	6.8	-367.1	60.0
chuet65321	6.8	156.2	120.0
Darfield	7	576.5	138.7
Iwate	6.9	245.5	60.0
Capemend	6.5	-265.3	28.7
Impvall	6.5	-168.3	63.8
Landers	7.3	273.6	44.0
Lomap	6.9	-151.9	40.0

Table 2-1 shows the details of the 10-ground motion used in this research before scaling. Below are 10 different ground motions that were scaled with Vancouver response spectrum using ETABS matching time history with the response spectrum option; it was matched in time domain [23, 18].

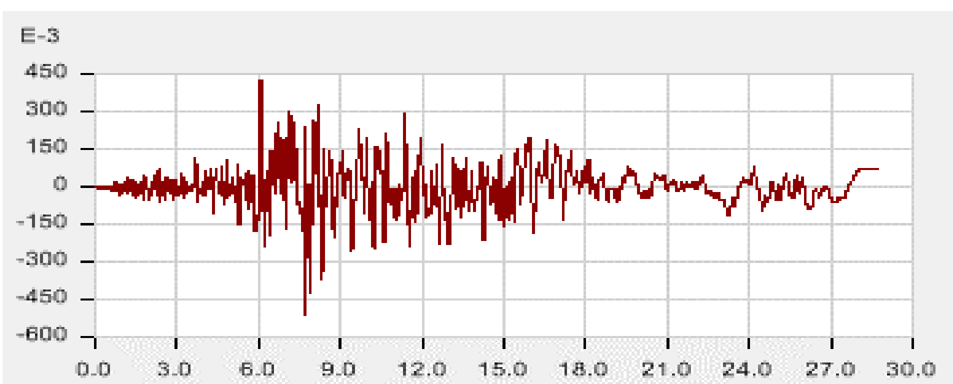


Figure 2-14 Cape Mendocino, 4/25/1992, Loleta Fire Station, 270

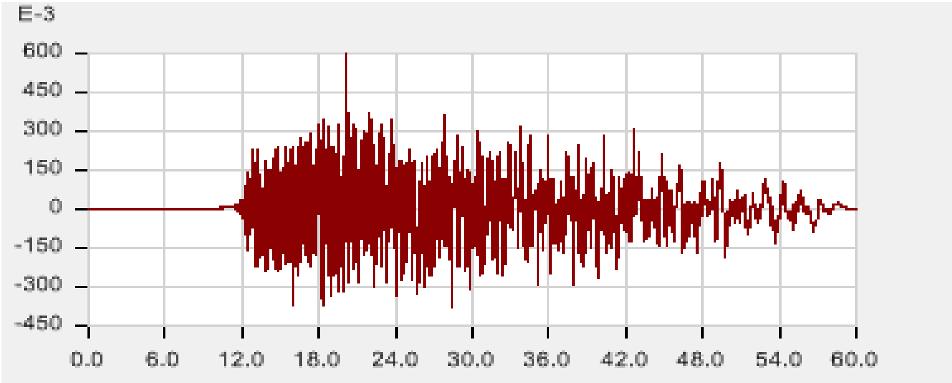


Figure 2-15 Chuetsu-oki, 7/16/2007, Joetsu Ogataku, EW

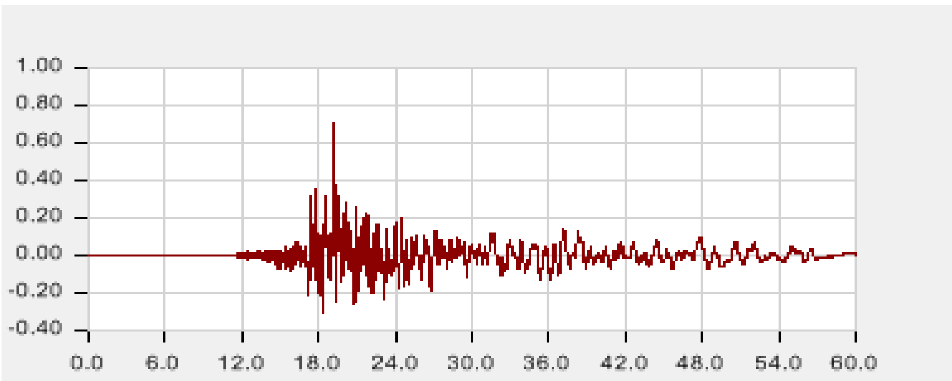


Figure 2-16 Chuetsu-oki, 7/16/2007, Yoshikawaku Joetsu City, EW

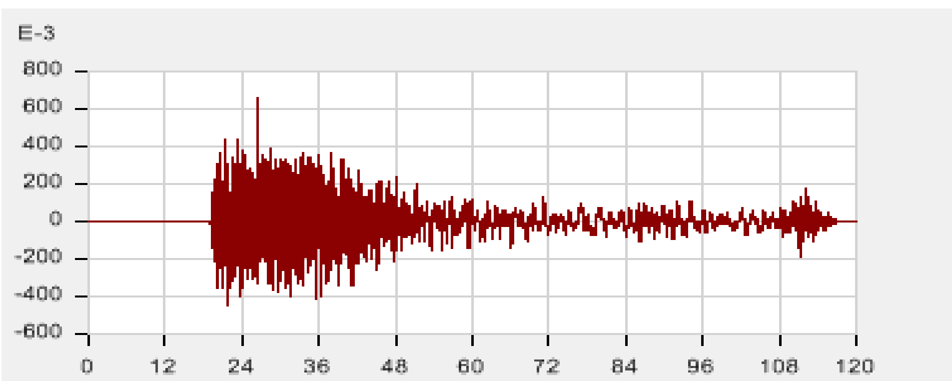


Figure 2-17 Chuetsu-oki, 7/16/2007, Ojiya City, UD

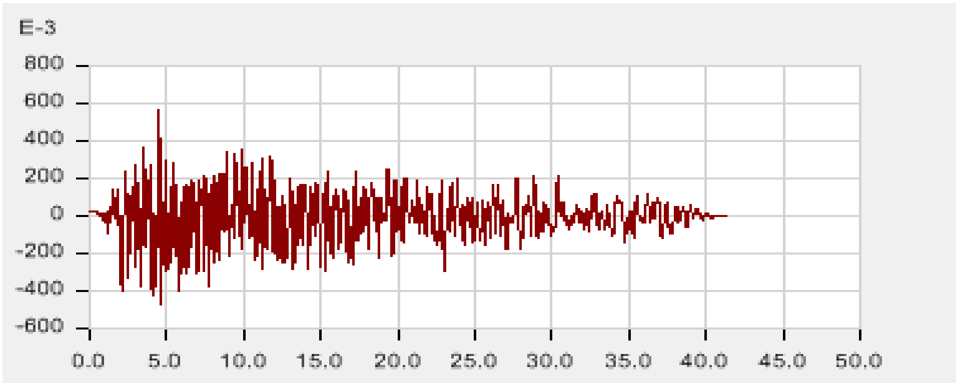


Figure 2-18 Corinth Greece, 2/24/1981, Corinth, L

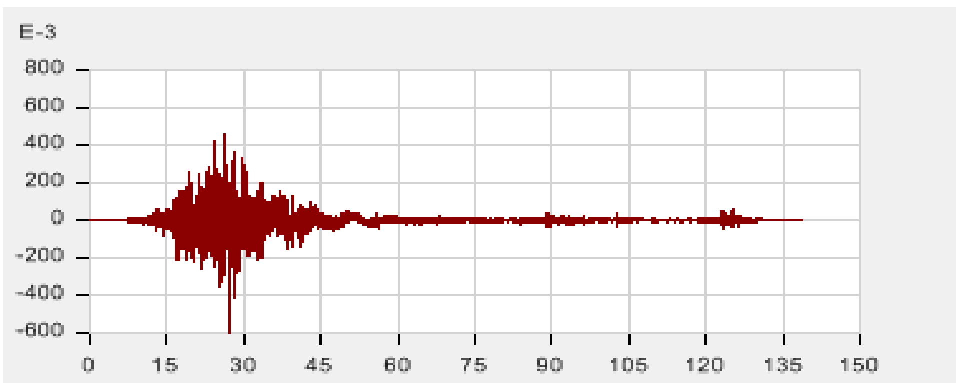


Figure 2-19 Darfield New Zealand, 9/3/2010, Heathcote Valley Primary School, S26W

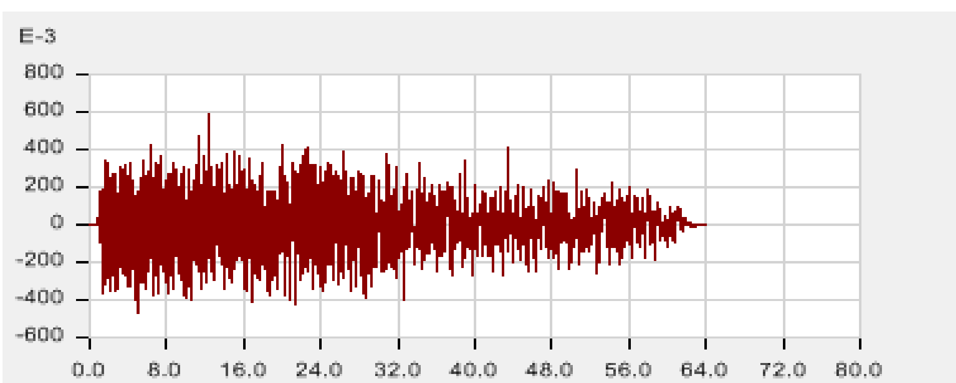


Figure 2-20 Imperial Valley-06, 10/15/1979, Cerro Prieto, 147

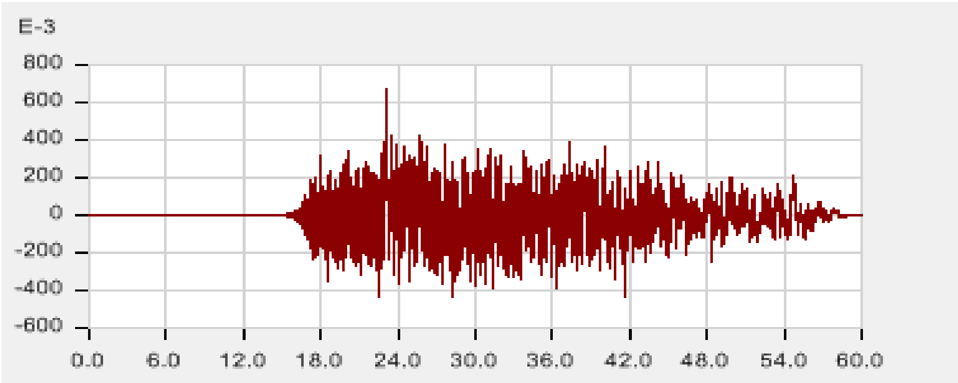


Figure 2-21 Iwate, 6/13/2008, Tamati Ono, EW

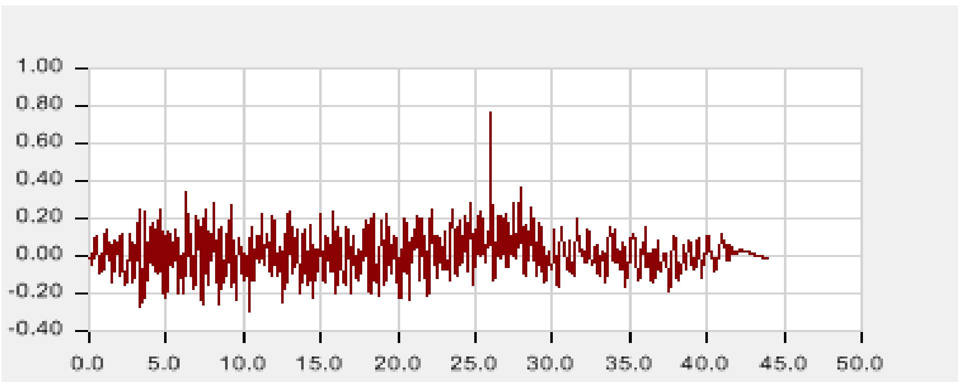


Figure 2-22 Landers, 6/28/1992, Joshua Tree, 0

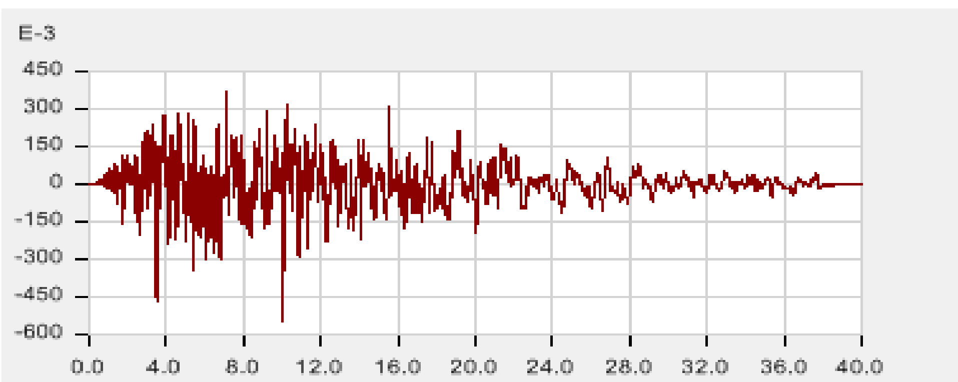


Figure 2-23 Loma Prieta, 10/18/1989, Coyote Lake Dam - Southwest Abutment, 195

Chapter 3 Design of the building

In this chapter, a description of different 3D models and the results for the static analysis will be described. For each case, a design was performed to determinate the section size and reinforcements depending on the behavior of the building and codes. Buildings were designed depending on the ductility and the presence of friction dampers. In the previous chapter, a description of the general core of the models was presented. However, every building has its property that will be described and developed. Afterwards, a discussion on the analysis of every different case will be made, by observing the behavior of shear and moment forces acting on the structures. Those behaviors will be put as a comparison tool between buildings with the same ductility to be able to determine the behavior of friction dampers in a static analysis. The economic analysis will also be conducted and describe in detail in this chapter.

3.1 Elastic model (EL)

This first model was designed with as an elastic structure using R_d=R_o=1.0. This model section was designed using trial and error to find the most economical design that was passing all the required code requirements and seismic provisions for an elastic building. The final sections of the beams and columns are given in Table 3-1. The reinforcements were also designed following the Canadian Handbook of Concrete buildings. Hand calculations were made and compared to ETABS results to make sure that the reinforcement details obtained using ETABS are accurate.

Table 3-1 section detail for model *(EL)*: elastic ductility

<table>
<tr><th></th><th colspan="3">COLUMNS</th><th colspan="2">BEAMS</th></tr>
<tr><td></td><td>corner</td><td>external</td><td>internal</td><td>external</td><td>internal</td></tr>
<tr><td>Story</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B*H mm</td><td>B*H mm</td></tr>
<tr><td>14</td><td rowspan="4">600</td><td rowspan="2">700</td><td rowspan="2">800</td><td>B600*500</td><td>B700*600</td></tr>
<tr><td>13</td><td>B650*550</td><td rowspan="2">B850*700</td></tr>
<tr><td>12</td><td rowspan="3">850</td><td rowspan="2">950</td><td rowspan="3">B700*600</td></tr>
<tr><td>11</td><td rowspan="3">B950*850</td></tr>
<tr><td>10</td><td rowspan="3">650</td><td>1000</td></tr>
<tr><td>9</td><td rowspan="2">1000</td><td rowspan="2">1100</td><td>B750*650</td></tr>
<tr><td>8</td><td rowspan="2">B800*650</td><td rowspan="2">B1000*800</td></tr>
<tr><td>7</td><td rowspan="3">700</td><td rowspan="2">1100</td><td rowspan="3">1200</td></tr>
<tr><td>6</td><td rowspan="6">B850*700</td><td rowspan="6">B1100*950</td></tr>
<tr><td>5</td><td rowspan="2">1200</td></tr>
<tr><td>4</td><td rowspan="3">750</td><td rowspan="3">1350</td></tr>
<tr><td>3</td><td rowspan="2">1350</td></tr>
<tr><td>2</td></tr>
<tr><td>1</td><td>1000</td><td>1500</td><td>1700</td></tr>
</table>

Reinforcement details are included in the appendix A. For this model, a linear static analysis was conducted using the load combinations included in the methodology. Figure 3-1 and table 3-2 show the earthquake load applies to the structure, and it was designed as a seismic load pattern NBCC2010, for a chosen location of Vancouver. Here, earthquake load governs in comparison to the wind load. The building is symmetrical and have the same earthquake load applied on both directions. Eccentricity of 0.1 was assumed.

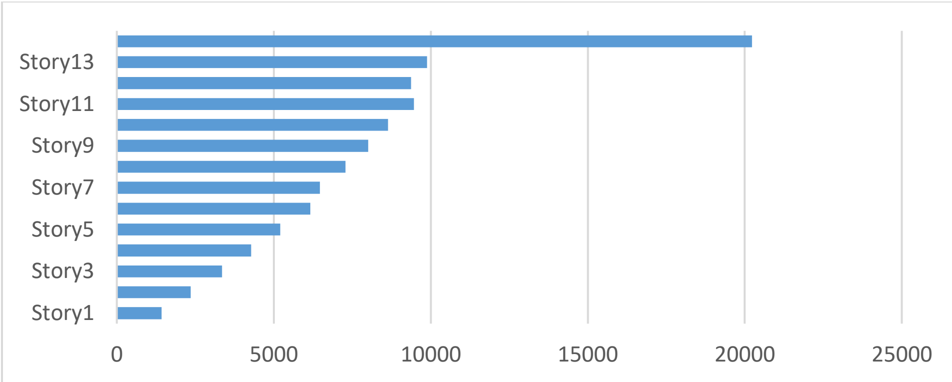


Figure 3-1 Lateral load applied on model *(EL)*

Table 3-2 Earthquake load applied on model *(EL)*: elastic

Story	**Elevation**	**X-Dir**	**Y-Dir**
	m	kN	kN
Story14	50	20227.4	20227.4
Story13	46.5	9882.3	9882.3
Story12	43	9370.1	9370.1
Story11	39.5	9461.0	9461.0
Story10	36	8641.5	8641.5
Story9	32.5	8008.4	8008.4
Story8	29	7283.0	7283.0
Story7	25.5	6468.5	6468.5
Story6	22	6159.8	6159.8
Story5	18.5	5207.0	5207.0
Story4	15	4276.8	4276.8
Story3	11.5	3347.8	3347.8
Story2	8	2353.9	2353.9
Story1	4.5	1421.8	1421.8

Following the code NBCC part 4, for the lateral deflection show on table 3-3, the maximum drift should be less than 2.5%*h on every floor.

Table 3-3 Drift for model *(EL)*: elastic ductility

Story	**DRIFT**	**<2.5%**
Story14	0.93%	TRUE
Story13	1.15%	TRUE
Story12	1.13%	TRUE
Story11	1.21%	TRUE
Story10	1.29%	TRUE
Story9	1.26%	TRUE
Story8	1.28%	TRUE
Story7	1.16%	TRUE
Story6	1.10%	TRUE
Story5	1.08%	TRUE
Story4	1.04%	TRUE
Story3	0.97%	TRUE
Story2	0.79%	TRUE
Story1	0.36%	TRUE

3.2 Elastic model with dampers (EL-D)

Elastic model with damper included eight dampers by floors. Four dampers in each direction. At first, the dampers as displayed in figure 3-2 are design for every floor using the lateral shear force and floor stiffness of the Elastic model (EL). The methodology for designing dampers can be found in the previous chapter. Dampers are included in a diagonal brace that will be connected at two joins. Earthquake induces force on dampers will be around 25-35% of the earthquake forces applied on each floor.

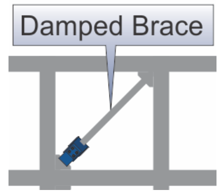


Figure 3-2 Damped brace included into a frame

Table 3-4 dampers detail for model *(EL-D)*: elastic frame including dampers

Story	Stiffness (kN/m)	Trans. Yield (kN)	Stiffness Ratio	Yield Exponent	Mass (kg)	Weight (kN)
14	262721	1620	0.0001	10	1136	11.15
13	352721	2400			1676	16.44
12	387076	3190			1750	17.17
11	515339	4010			2338	22.93
10	568018	4760			2614	25.64
9	689408	5490			3149	30.9
8	755830	6170			3668	35.98
7	824542	6770			3842	37.69
6	911577	7330			4067	39.9
5	964256	7790			4553	44.67
4	1005483	8180			4611	45.23
3	1026096	8480			4795	47.04
2	1101679	8690			5086	49.89
1	1581910	9260			6798	66.69

In Table 3-4 the mass and the weight include the braces self-weight and mass.

Table 3-5 story forces taken by dampers at every floor for model *(EL-D)*: elastic frame including dampers

Story	Slip force 1 dampers (kN)	Horizontal projection Slip force 1 dampers (kN)	Story forces (kN)	F_d/F_s (%)
14	1620	1768	20227	35%
13	2400	2620	30110	35%
12	3190	3482	39480	35%
11	4010	4377	48941	36%
10	4760	5196	57582	36%
9	5490	5992	65591	37%
8	6170	6735	72874	37%
7	6770	7390	79342	37%
6	7330	8001	85502	37%
5	7790	8503	90709	37%
4	8180	8929	94986	38%
3	8480	9256	98334	38%
2	8690	9485	100688	38%
1	9260	10796	102109	42%

After designing the dampers, they were applied on an exact copy of the elastic model (EL) and was modified by reduction of the members; columns and beams were optimized to obtain a cost-effective model. It was noticed that when the dampers are included in the building, members will be significantly reduced in size. The same verifications following the Canadian code were applied to the model. Table 3-4 shown the final dampers design and Table 3-5 shows the story forces taken by dampers at each floor. Four dampers are present on each direction at each floor and they were assumed to take about 30% of the story forces when designed, and it is in accordance with Table 3-5 that shows that in average they take a same order of force or slightly more, about 37%. The table shows the percentage of story forces taken by one dampers in each floor. The dampers were modelled with a non-linear property and analyzed by non-linear static analysis. As verification, to observe if the dampers are activated, the axial force on the braces must be determined and compared to the slip force. The final sectional dimensions of the structural members are shown in the Table 3-6:

Table 3-6 sections detail for model *(EL-D)*: elastic model with dampers

<table>
<tr><th rowspan="2"></th><th colspan="4">COLUMNS</th><th colspan="2">BEAMS</th></tr>
<tr><th>corner</th><th>external</th><th>internal</th><th>Internal
Connected dampers</th><th>external</th><th>internal</th></tr>
<tr><td>Story</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B*H mm</td><td>B*H mm</td></tr>
<tr><td>Story14</td><td rowspan="3">500</td><td rowspan="2">600</td><td rowspan="2">700</td><td rowspan="2">700</td><td>B550*450</td><td>B650*550</td></tr>
<tr><td>Story13</td><td rowspan="5">B650*550</td><td>B750*650</td></tr>
<tr><td>Story12</td><td rowspan="2">650</td><td rowspan="2">800</td><td rowspan="2">800</td><td>B800*700</td></tr>
<tr><td>Story11</td><td rowspan="4">600</td><td rowspan="2">B850*750</td></tr>
<tr><td>Story10</td><td rowspan="2">700</td><td rowspan="2">850</td><td rowspan="2">850</td></tr>
<tr><td>Story9</td><td rowspan="4">B900*800</td></tr>
<tr><td>Story8</td><td rowspan="2">800</td><td rowspan="2">950</td><td rowspan="2">950</td><td rowspan="2">B750*650</td></tr>
<tr><td>Story7</td><td rowspan="3">650</td></tr>
<tr><td>Story6</td><td rowspan="2">850</td><td rowspan="2">1050</td><td rowspan="2">1050</td><td rowspan="6">B800*700</td></tr>
<tr><td>Story5</td><td rowspan="2">B950*850</td></tr>
<tr><td>Story4</td><td rowspan="3">700</td><td rowspan="2">900</td><td rowspan="2">1150</td><td rowspan="2">1150</td></tr>
<tr><td>Story3</td><td rowspan="3">B1000*800</td></tr>
<tr><td>Story2</td><td>1050</td><td>1250</td><td>1250</td></tr>
<tr><td>Story1</td><td>950</td><td>1250</td><td>1400</td><td>1400</td></tr>
</table>

Reinforcement details are included in the appendix A. The Earthquake force applied to the second model was taken as a "user load" force and the ground motion from model (EL) was applied. The drift as shown in Table 3-7 was also taken into consideration and passed the NBCC code.

Table 3-7 drift for model *(EL-D)*: elastic model with dampers

Story	DRIFT	<2.5%
Story14	0.75%	TRUE
Story13	0.93%	TRUE
Story12	0.95%	TRUE
Story11	1.06%	TRUE
Story10	1.08%	TRUE
Story9	1.11%	TRUE
Story8	1.05%	TRUE
Story7	1.08%	TRUE
Story6	1.01%	TRUE
Story5	0.99%	TRUE
Story4	0.92%	TRUE
Story3	0.87%	TRUE
Story2	0.69%	TRUE
Story1	0.34%	TRUE

3.2.1 Comparison between the model (EL) Elastic and model (EL-D) elastic with dampers

Moment

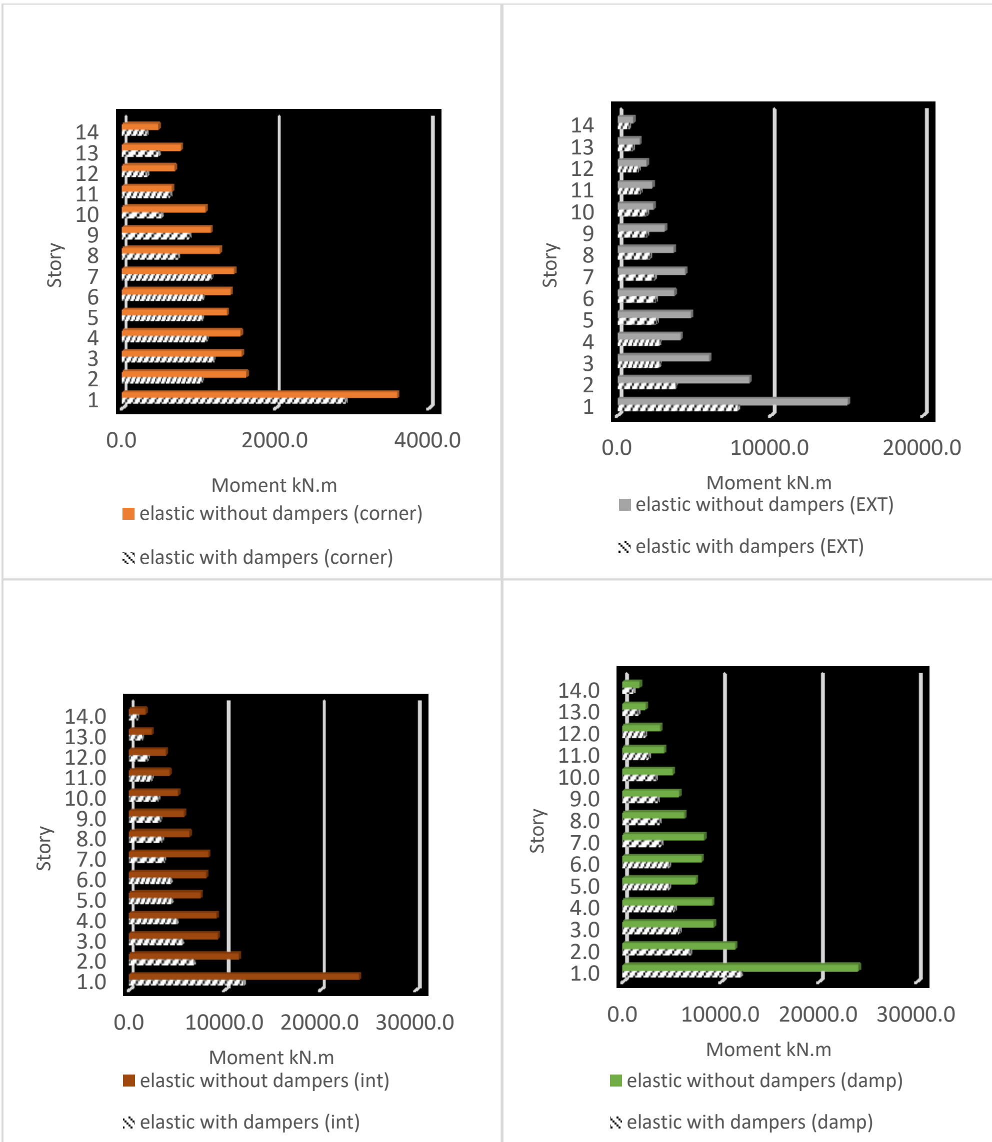


Figure 3-3 moment columns comparisons between model *(EL)* & *(EL-D)*: (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a dampers

Table 3-8 moment comparisons detail for model *(EL-D)*: elastic model with dampers

		Elastic with DAMPERS M (kN.m)	**Elastic M (kN.m)**	**difference**			**COLUMN WEIGHT /EACH FLOOR kN**		
14	C	312.2	464.3	32.8%	3.6%	34.9%	1639.7	3.1%	1.1%
	EXT	725.0	1009.7	28.2%	12.5%				
	INT	814.8	1659.6	50.9%	5.7%				
	Damp	1007.9	1659.6	39.3%	13.1%				
13	C	463.8	762.6	39.2%	4.4%	34.5%	1639.7	3.1%	1.1%
	EXT	989.2	1428.8	30.8%	13.7%				
	INT	1318.0	2314.6	43.1%	4.8%				
	Damp	1505.4	2314.6	35.0%	11.7%				
12	C	317.3	678.6	53.2%	5.9%	38.5%	2305.0	4.4%	1.7%
	EXT	1317.4	1877.5	29.8%	13.3%				
	INT	1894.9	3782.4	49.9%	5.5%				
	Damp	2222.2	3782.4	41.3%	13.8%				
11	C	615.9	641.4	4.0%	0.4%	34.5%	2305.0	4.4%	1.5%
	EXT	1437.9	2252.1	36.2%	16.1%				
	INT	2276.3	4182.4	45.6%	5.1%				
	Damp	2563.8	4182.4	38.7%	12.9%				
10	C	503.5	1081.7	53.5%	5.9%	30.1%	2457.0	4.7%	1.4%
	EXT	1906.9	2324.9	18.0%	8.0%				
	INT	2931.9	5049.9	41.9%	4.7%				
	Damp	3300.2	5049.9	34.6%	11.5%				
9	C	868.7	1149.9	24.4%	2.7%	37.7%	3112.2	6.0%	2.3%
	EXT	1893.7	3078.1	38.5%	17.1%				
	INT	3176.8	5708.9	44.4%	4.9%				
	Damp	3491.8	5708.9	38.8%	12.9%				
	C	714.9	1268.5	43.6%	4.8%				

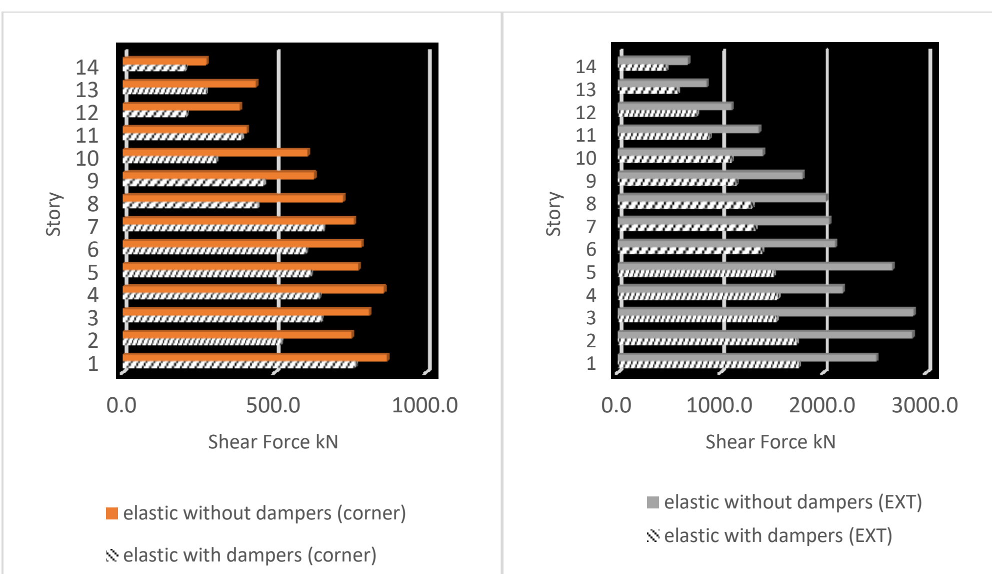
8	EXT	2114.6	3648.0	42.0%	18.7%	42.3%	3112.2	6.0%	2.5%
	INT	3339.6	6246.6	46.5%	5.2%				
	Damp	3696.4	6246.6	40.8%	13.6%				
7	C	1152.9	1454.2	20.7%	2.3%	46.6%	3726.2	7.1%	3.3%
	EXT	2374.9	4397.7	46.0%	20.4%				
	INT	3617.7	8241.3	56.1%	6.2%				
	Damp	3893.6	8241.3	52.8%	17.6%				
6	C	1045.1	1410.8	25.9%	2.9%	36.5%	3726.2	7.1%	2.6%
	EXT	2486.2	3683.3	32.5%	14.4%				
	INT	4280.5	8002.6	46.5%	5.2%				
	Damp	4647.9	8002.6	41.9%	14.0%				
5	C	1034.2	1362.0	24.1%	2.7%	40.6%	4035.4	7.7%	3.1%
	EXT	2536.7	4785.0	47.0%	20.9%				
	INT	4368.0	7432.3	41.2%	4.6%				
	Damp	4656.5	7432.3	37.3%	12.4%				
4	C	1090.9	1539.3	29.1%	3.2%	37.8%	4573.8	8.8%	3.3%
	EXT	2712.8	4110.1	34.0%	15.1%				
	INT	4879.9	9091.6	46.3%	5.1%				
	Damp	5189.5	9091.6	42.9%	14.3%				
3	C	1181.7	1553.5	23.9%	2.7%	44.2%	5087.9	9.8%	4.3%
	EXT	2704.1	5970.3	54.7%	24.3%				
	INT	5507.5	9220.9	40.3%	4.5%				
	Damp	5700.5	9220.9	38.2%	12.7%				
2	C	1029.8	1613.8	36.2%	4.0%	47.2%	5087.9	9.8%	4.6%
	EXT	3748.2	8596.1	56.4%	25.1%				
	INT	6695.1	11439.7	41.5%	4.6%				
	Damp	6815.8	11439.7	40.4%	13.5%				
1	C	2909.7	3582.1	18.8%	2.1%	45.8%	9313.9	17.9%	8.2%
	EXT	7811.7	15056.5	48.1%	21.4%				

	INT	11906.3	24004.2	50.4%	5.6%				
	Damp	11979.8	24004.2	50.1%	16.7%				
				39.1%			52122.0		41.1%

Table 3-8 shows the comparison of the moment applied to the columns between the two models: elastic (EL) and elastic-dampers (EL-D). The difference in the moment applied on the columns between the two models and the weight distribution of the different type of columns by floors are shown in Figure 3-3. Four different type of columns was determinate: four corner columns, sixteen external columns, four internal columns and twelve columns that are related to dampers. It is observed that moments on the beams and columns have reduced by about 41% when dampers are used.

Shear Force

It was found as shown on Figure 3-4, that friction dampers have an influence on a structure's shear force. A comparison between columns of both models was made, and a decrease of about 36.6% of the shear force was found in model (EL-D); an elastic model with dampers.



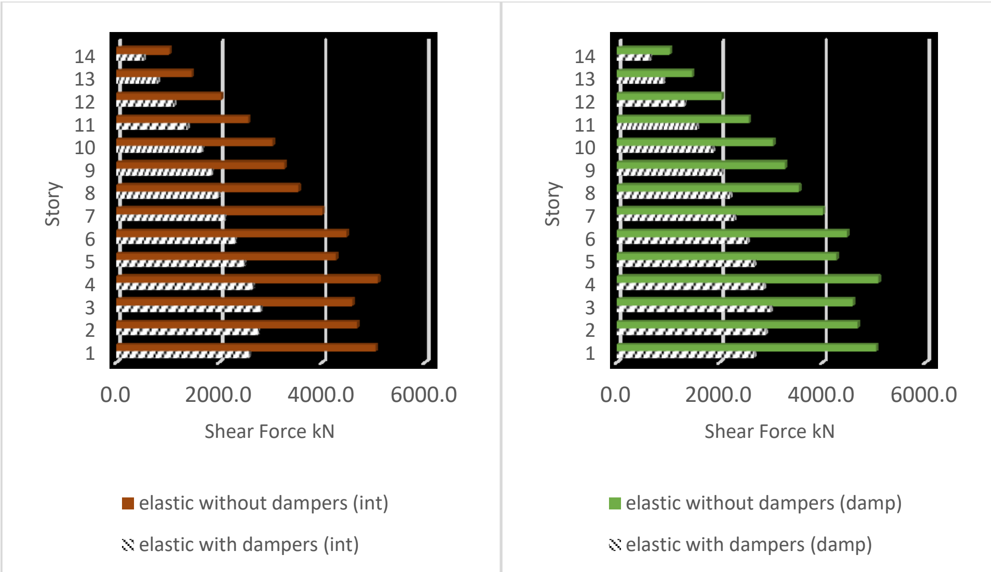


Figure 3-4 Shear force columns comparisons between model *(EL)* & *(EL-D)*: (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a dampers.

In summary, it was observed that the use of dampers into an elastic building help reducing the moment and shear force on the building. When a building is subjected to less shear and moment force, it will be less subjected to deterioration due to seismic influence, and the building will be considered to have a longer life as there will be less impact on the actual structure. Dampers can take about 30-40% earthquake force, as the dampers designed.

3.3 Moderately-ductile model (MD)

The third model was designed with a ductility of moderately-ductile (R_o= 1.4 and R_d= 2.5), NBCC chapter 4, part B. table 4.18.9, without any dissipation devices.

The details of seismic provision for moderately-ductile MRF concrete structure can be found in detail in the Canadian concrete handbook 2014: section 21.7.2.

Table 3-9 section detail for model *(MD)*: moderately-ductile ductility

	COLUMNS			**BEAMS**	
	corner	external	internal	external	internal
Story	B=H mm	B=H mm	B=H mm	B*H mm	B*H mm
14	500	600	650	B500X350	B550X400

<table>
<tr><td>13</td><td></td><td></td><td></td><td>B550X400</td><td>B650X450</td></tr>
<tr><td>12</td><td rowspan="3">550</td><td rowspan="3">700</td><td rowspan="3">750</td><td rowspan="4">B650X450</td><td rowspan="2">B700X500</td></tr>
<tr><td>11</td></tr>
<tr><td>10</td><td rowspan="2">B750X600</td></tr>
<tr><td>9</td><td rowspan="2">600</td><td rowspan="2">750</td><td rowspan="2">800</td></tr>
<tr><td>8</td><td rowspan="8">B700X500</td><td rowspan="5">B800X650</td></tr>
<tr><td>7</td><td rowspan="3">650</td><td rowspan="3">850</td><td rowspan="3">900</td></tr>
<tr><td>6</td></tr>
<tr><td>5</td></tr>
<tr><td>4</td><td rowspan="3">700</td><td rowspan="3">950</td><td rowspan="3">1000</td></tr>
<tr><td>3</td><td rowspan="3">B850X700</td></tr>
<tr><td>2</td></tr>
<tr><td>1</td><td>850</td><td>1200</td><td>1300</td></tr>
</table>

Table 3-9 represented the section of beams and columns used for designing the model (MD).

Table 3-10 drift for model *(MD)*: moderately-ductile ductility

	Drift	**Drift*2.5*1.4**	**<2.5%**
Story14	0.48%	1.68%	TRUE
Story13	0.56%	1.95%	TRUE
Story12	0.56%	1.97%	TRUE
Story11	0.60%	2.11%	TRUE
Story10	0.63%	2.21%	TRUE
Story9	0.62%	2.17%	TRUE
Story8	0.63%	2.20%	TRUE
Story7	0.62%	2.18%	TRUE

Story6	0.65%	2.27%	TRUE
Story5	0.66%	2.31%	TRUE
Story4	0.61%	2.13%	TRUE
Story3	0.55%	1.92%	TRUE
Story2	0.42%	1.48%	TRUE
Story1	0.17%	0.61%	TRUE

Table 3-10 confirms that the model (MD) was designed to pass the drift limits at every floor.

Table 3-11 Earthquake load applied on model *(MD)*: moderately-ductile ductility

Story	**Elevation**	**X-Dir**	**Y-Dir**
	m	kN	kN
Story14	50	4187.3	4187.3
Story13	46.5	1604.7	1604.7
Story12	43	1567.7	1567.7
Story11	39.5	1458.3	1458.3
Story10	36	1389.5	1389.5
Story9	32.5	1260.8	1260.8
Story8	29	1180.7	1180.7
Story7	25.5	1048.5	1048.5
Story6	22	916.9	916.9
Story5	18.5	771.0	771.0
Story4	15	632.2	632.2
Story3	11.5	505.9	505.9
Story2	8	351.9	351.9
Story1	4.5	212.0	212.0

A table 3-11 show the load pattern for Vancouver, and the final load was calculated by ETABS is also weight dependent. The model (MD) was designed to obtain the most optimized structure possible with the lowest ratio of steel allowed by codes. The ratio between concrete amount and steel used was also taking into consideration.

3.4 Moderately-ductile model with dampers (MD-D)

The fourth model was designed using the same method for damper design and selection of beam and columns size as the model (EL-D). Table 3-12 shows the final dampers design and Table 3-13 shows the story forces taken by dampers at each floor. Four dampers are present on each direction by floor and they were assumed to take about 30% of the story forces when designed, and it is accordance with Table 3-13 that shows that in average they take a slightly more shear with about 37%. Table 3-15 displays that the sizes of the columns and beams are smaller than moderately ductile model (MD). In table 3-14, drift was also verified following the NBCC part 4 code.

Table 3-12 dampers details for model (MD-D): moderately-ductile structure with dampers

Story	Stiffness (kN/m)	Trans. Yield (kN)	Stiffness Ratio	Yield Exponent	Mass (kg)	Weight (kN)
14	165835	345			837	8.2
13	165835	490			845	8.3
12	209831	622			955	9.4
11	216088	745			889	8.7
10	216088	857			875	8.6
9	247216	962			952	9.3
8	252310	1057	0.0001	10	973	9.5
7	278602	1142			1037	10.2
6	298884	1215			1090	10.7
5	320947	1279			1109	10.9
4	343581	1332			1139	11.2
3	358761	1373			1161	11.4
2	415800	1402			1211	11.9

1	655822	1500			1380	13.5

Table 3-13 story forces taken by dampers at every floor for model *(MD-D)*: moderately-ductile structure including dampers

Story	**Slip force 1 dampers (kN)**	**Horizontal projection Slip force 1 dampers (kN)**	**Story forces (kN)**	**F_d/F_s (%)**
14	345	377	4187	36%
13	490	535	1605	37%
12	622	679	1568	37%
11	745	813	1458	37%
10	857	935	1390	37%
9	962	1050	1261	37%
8	1057	1154	1181	36%
7	1142	1247	1050	36%
6	1215	1326	917	36%
5	1279	1396	771	36%
4	1332	1454	633	36%
3	1373	1499	506	36%
2	1402	1530	352	36%
1	1500	1749	212	41%

Table 3-14 drift for model (MD-D): moderately-ductile ductility with dampers

	Drift	Drift*2.5*1.4	<2.5%
Story14	0.52%	1.82%	TRUE
Story13	0.63%	2.19%	TRUE
Story12	0.61%	2.12%	TRUE
Story11	0.69%	2.40%	TRUE
Story10	0.69%	2.41%	TRUE
Story9	0.63%	2.20%	TRUE
Story8	0.67%	2.36%	TRUE
Story7	0.67%	2.33%	TRUE
Story6	0.70%	2.43%	TRUE
Story5	0.71%	2.48%	TRUE
Story4	0.68%	2.39%	TRUE
Story3	0.66%	2.29%	TRUE
Story2	0.53%	1.87%	TRUE
Story1	0.22%	0.76%	TRUE

Table 3-15 sections details for model (MD-D): moderately-ductile ductility with dampers

<table>
<tr><th></th><th colspan="4">COLUMNS</th><th colspan="2">BEAMS</th></tr>
<tr><td></td><td>corner</td><td>external</td><td>internal</td><td>internal connected dampers</td><td>external</td><td>internal</td></tr>
<tr><td>Story</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B*H mm</td><td>B*H mm</td></tr>
<tr><td>Story14</td><td rowspan="2">400</td><td rowspan="2">500</td><td rowspan="2">550</td><td rowspan="2">550</td><td>B450*350</td><td>B500*400</td></tr>
<tr><td>Story13</td><td rowspan="3">B500*400</td><td>B550*400</td></tr>
<tr><td>Story12</td><td rowspan="2">450</td><td rowspan="2">550</td><td rowspan="2">650</td><td rowspan="2">650</td><td rowspan="2">B650*500</td></tr>
<tr><td>Story11</td></tr>
</table>

<table>
<tr><td>Story10</td><td></td><td></td><td></td><td></td><td rowspan="6">B600*500</td><td></td></tr>
<tr><td>Story9</td><td rowspan="3">500</td><td rowspan="2">600</td><td rowspan="2">700</td><td rowspan="2">700</td><td rowspan="9">B700*600</td></tr>
<tr><td>Story8</td></tr>
<tr><td>Story7</td><td rowspan="3">650</td><td rowspan="3">800</td><td rowspan="3">800</td></tr>
<tr><td>Story6</td><td rowspan="3">550</td></tr>
<tr><td>Story5</td></tr>
<tr><td>Story4</td><td rowspan="3">700</td><td rowspan="3">850</td><td rowspan="3">850</td><td rowspan="4">B650*500</td></tr>
<tr><td>Story3</td><td rowspan="2">600</td></tr>
<tr><td>Story2</td></tr>
<tr><td>Story1</td><td>750</td><td>1000</td><td>1100</td><td>1100</td></tr>
</table>

3.4.1 Comparison between the model (MD) Moderately-ductile and model (MD-D) Moderately-ductile with dampers

Moment

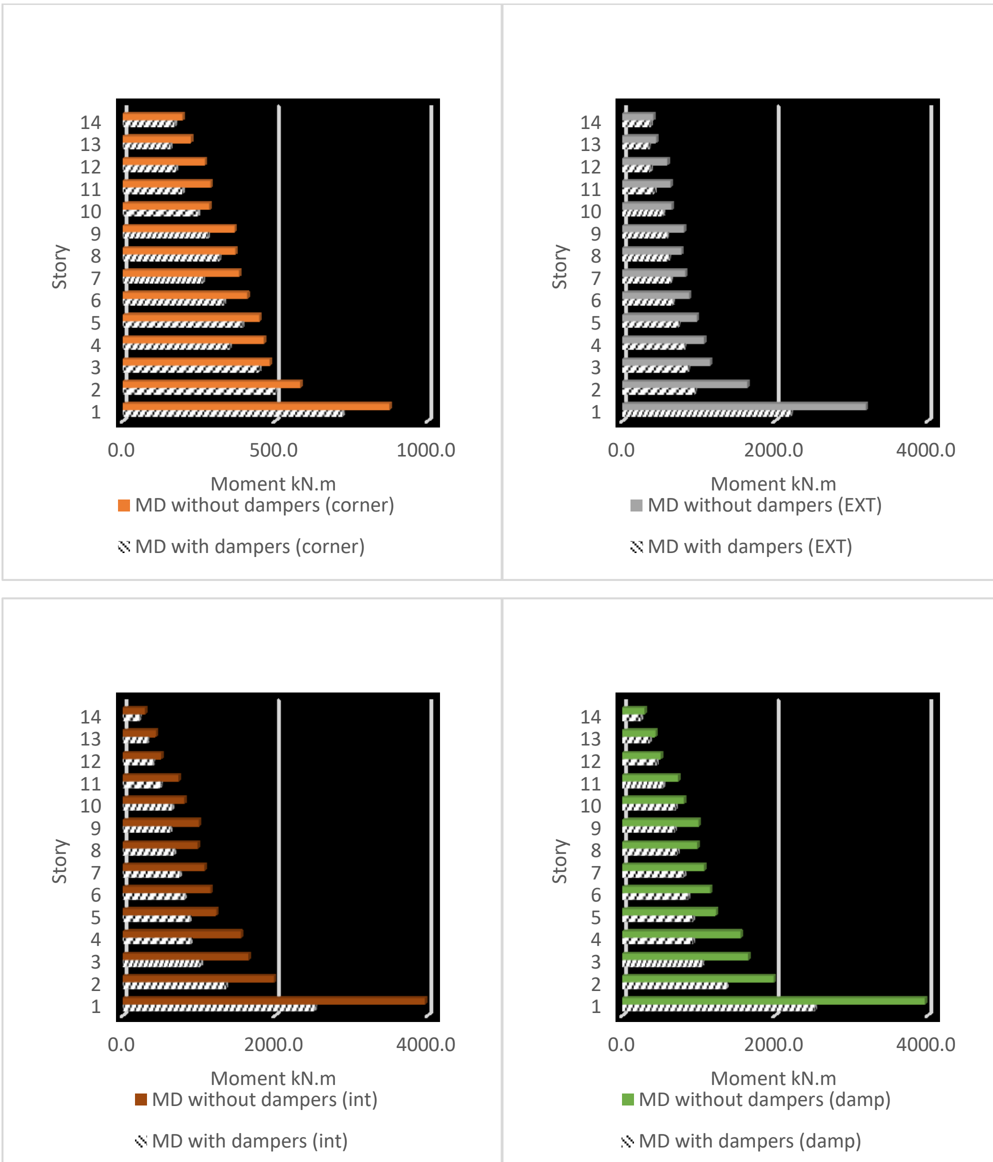


Figure 3-5 moment columns comparisons between model (MD) & (MD-D): (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a dampers.

Figure 3-5 shows that the moment distribution in the model (MD) is more significant than in the model (MD-D).

Dampers were designed to dissipate around 30% of the seismic load. The average difference between the two models his about 27.6% less moment applied on columns for the model (MD-D) using dampers into their design.

Shear Force

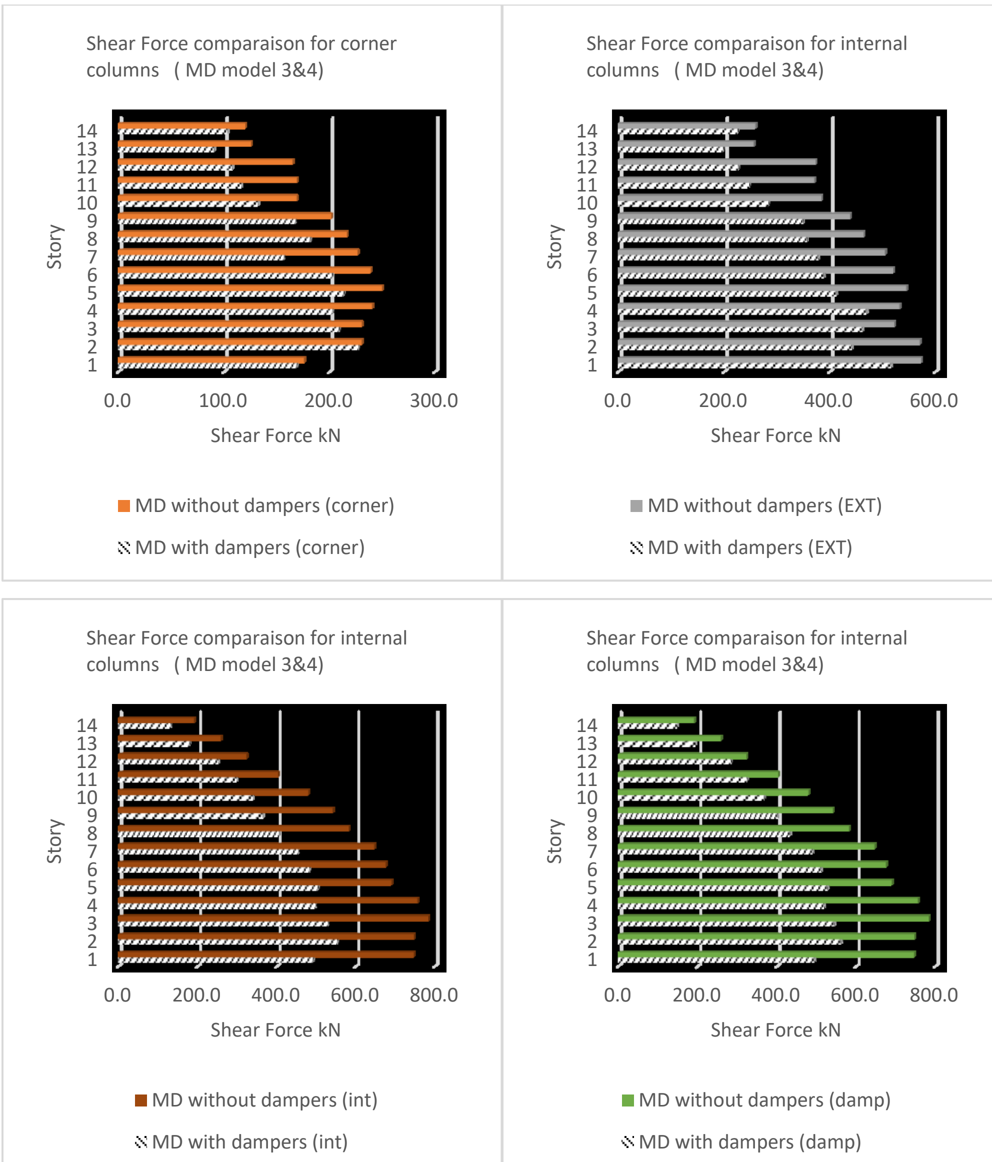


Figure 3-6 Shears Force columns comparisons between model (MD) & (MD-D): (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a dampers.

Figure 3-6, illustrates that the shear force applied on the columns is 22.8% less on model (MD-D). It can be concluded that dampers get activated and can slip under seismic load and can dissipate around 30% of energy applied on the structure.

3.5 Ductile Model (DUC)

The final model (DUC) was designed using the same core details as the previous model and was design using as a ductile frame. Special seismic provisions are needed for ductile design in the Canadian concrete handbook 2014: section 21.4. It was also design with R_o= 1.7 and R_d= 4.0, NBCC Chapter 4, part B. Table 4.18.9.

The final section member, reinforcement details can be found in the appendix A. The drift required follow the NBCC part 4 codes. The final earthquake load was determinate by load pattern using ETABS and NBCC2010. Similar steps as the previous model was made to analyses the model. Final section members, the static load pattern applied to the structure and the drift can be found respectively on Tables 3-16, 3-17 and 3-18.

Table 3-16 sections details for model (DUC): ductile frame

<table>
<tr><th></th><th colspan="3">COLUMNS</th><th colspan="2">BEAMS</th></tr>
<tr><td></td><td>corner</td><td>external</td><td>internal</td><td>external</td><td>internal</td></tr>
<tr><td>Story</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B*H mm</td><td>B*H mm</td></tr>
<tr><td>Story14</td><td rowspan="2">550</td><td rowspan="2">600</td><td rowspan="2">650</td><td>B500*450</td><td>B500*450</td></tr>
<tr><td>Story13</td><td>B600*500</td><td rowspan="2">B600*500</td></tr>
<tr><td>Story12</td><td rowspan="3">600</td><td rowspan="3">650</td><td rowspan="3">700</td><td rowspan="3">B650*550</td></tr>
<tr><td>Story11</td><td rowspan="2">B650*550</td></tr>
<tr><td>Story10</td></tr>
<tr><td>Story9</td><td rowspan="3">650</td><td rowspan="2">700</td><td rowspan="3">800</td><td rowspan="4">B700*600</td><td rowspan="4">B700*600</td></tr>
<tr><td>Story8</td></tr>
<tr><td>Story7</td><td rowspan="4">750</td></tr>
<tr><td>Story6</td><td rowspan="3">700</td><td rowspan="3">850</td></tr>
<tr><td>Story5</td><td rowspan="5">B750*600</td><td rowspan="5">B750*600</td></tr>
<tr><td>Story4</td></tr>
<tr><td>Story3</td><td rowspan="3">750</td><td rowspan="3">800</td><td rowspan="2">900</td></tr>
<tr><td>Story2</td></tr>
<tr><td>Story1</td><td>1000</td></tr>
</table>

Table 3-17 Earthquake load applied on model (DUC): ductile frame

Story	Elevation	X-Dir	Y-Dir
	m	kN	kN
Story14	50	2067.1	2067.1
Story13	46.5	845.7	845.7
Story12	43	796.8	796.8
Story11	39.5	756.3	756.3
Story10	36	689.3	689.3
Story9	32.5	653.1	653.1
Story8	29	588.3	588.3
Story7	25.5	518.5	518.5
Story6	22	449.9	449.9
Story5	18.5	387.0	387.0
Story4	15	313.8	313.8
Story3	11.5	241.8	241.8
Story2	8	169.4	169.4
Story1	4.5	97.7	97.7

Table 3-18 drift for model (DUC): ductile frame

	Drift	Drift*4*1.7	<2.5%
Story14	0.23%	1.60%	TRUE
Story13	0.28%	1.90%	TRUE
Story12	0.30%	2.00%	TRUE
Story11	0.33%	2.20%	TRUE
Story10	0.34%	2.30%	TRUE
Story9	0.33%	2.20%	TRUE
Story8	0.35%	2.40%	TRUE

Story7	0.36%	2.40%	TRUE
Story6	0.35%	2.40%	TRUE
Story5	0.35%	2.40%	TRUE
Story4	0.35%	2.40%	TRUE
Story3	0.34%	2.30%	TRUE
Story2	0.31%	2.10%	TRUE
Story1	0.18%	1.20%	TRUE

3.6 Ductile Model with dampers (DUC-D)

This model was designed by using the ductile model (DUC) as the core model, and by adding friction dampers. The story stiffness and story shear forces of the model (DUC) was used to be able to determinate accurate dampers size. After those dampers where applied to the structure, a trial-and-error method was performed to reduce the member sections. Dampers were expected to slip under the design ground motion. The final sizes of model (DUC-D) section are shown on table 3-18, the final drift on table 3-19.

The final sizes of the dampers and the final sections of the beams and columns are included in Table 3-19 and 3-21. Table 3-20 shows the story forces taken by dampers at each floor. Four dampers are present on each direction by floor and were assumed to be taken about 30% of the story forces when designed, and it is in accordance with Table 3-20 that shows that in average they take a slightly more with about 36%.

Table 3-19 dampers details for model (DUC-D): ductile with dampers

Story	Stiffness (kN/m)	Trans. Yield (kN)	Stiffness Ratio	Yield Exponent	Mass (kg)	Weight (kN)
14	110500	150	0.0001	10	813	8
13	122366	250			829	8.1
12	122366	250			829	8.1
11	125000	350			837	8.21
10	169604	500			845	8.29
9	169604	500			845	8.29
8	175255	550			845	8.29
7	175255	550			845	8.29
6	216088	650			864	8.48
5	216088	650			864	8.48
4	228089	675			873	8.57
3	228089	675			873	8.57
2	261105	700			942	9.2
1	318125	750			1220	12

Table 3-20 story forces taken by dampers at every floor for model *(DUC-D)*: ductile structure including dampers

Story	Slip force 1 dampers (kN)	Horizontal projection Slip force 1 dampers (kN)	Story forces (kN)	F_d/F_s (%)
14	150	164	2067	32%
13	250	273	846	37%
12	250	273	797	29%

11	350	382	756	34%
10	500	546	689	42%
9	500	546	653	38%
8	550	600	588	38%
7	550	600	519	35%
6	650	709	450	39%
5	650	709	387	37%
4	675	737	314	37%
3	675	737	242	35%
2	700	764	169	36%
1	750	874	98	41%

Table 3-21 sections details for model (DUC-D): ductile ductility with dampers

<table>
<tr><td></td><td colspan="4">COLUMNS</td><td colspan="2">BEAMS</td></tr>
<tr><td></td><td>corner</td><td>external</td><td>internal</td><td>Internal connected dampers</td><td>external</td><td>internal</td></tr>
<tr><td>Story</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B=H mm</td><td>B*H mm</td><td>B*H mm</td></tr>
<tr><td>Story14</td><td rowspan="2">450</td><td rowspan="2">500</td><td rowspan="2">550</td><td rowspan="2">550</td><td>B450*450</td><td>B450*450</td></tr>
<tr><td>Story13</td><td rowspan="2">B550*450</td><td rowspan="2">B550*450</td></tr>
<tr><td>Story12</td><td rowspan="3">500</td><td rowspan="3">550</td><td rowspan="3">600</td><td rowspan="3">600</td></tr>
<tr><td>Story11</td><td rowspan="3">B600*500</td><td rowspan="2">B600*500</td></tr>
<tr><td>Story10</td></tr>
<tr><td>Story9</td><td rowspan="3">550</td><td rowspan="2">600</td><td rowspan="3">700</td><td rowspan="3">700</td><td rowspan="4">B650*550</td></tr>
<tr><td>Story8</td><td rowspan="3">B650*550</td></tr>
<tr><td>Story7</td><td rowspan="4">650</td></tr>
<tr><td>Story6</td><td rowspan="3">600</td><td rowspan="3">750</td><td rowspan="3">750</td></tr>
<tr><td>Story5</td><td rowspan="5">B700*600</td><td rowspan="5">B700*600</td></tr>
<tr><td>Story4</td></tr>
<tr><td>Story3</td><td rowspan="3">650</td><td rowspan="3">700</td><td rowspan="2">800</td><td rowspan="2">800</td></tr>
<tr><td>Story2</td></tr>
<tr><td>Story1</td><td>850</td><td>850</td></tr>
</table>

Table 3-22 drift for model (DUC-D): ductile ductility with dampers

	Drift	**1.7*4D**	
Story14	0.25%	1.70%	TRUE
Story13	0.32%	2.10%	TRUE
Story12	0.34%	2.30%	TRUE
Story11	0.36%	2.40%	TRUE
Story10	0.36%	2.40%	TRUE
Story9	0.33%	2.20%	TRUE
Story8	0.36%	2.40%	TRUE
Story7	0.37%	2.40%	TRUE
Story6	0.35%	2.30%	TRUE
Story5	0.33%	2.20%	TRUE
Story4	0.34%	2.30%	TRUE
Story3	0.32%	2.20%	TRUE
Story2	0.31%	2.10%	TRUE
Story1	0.20%	1.30%	TRUE

3.6.1 Comparison between the model (DUC) Ductile and model (DUC-D) Ductile with dampers

Moment

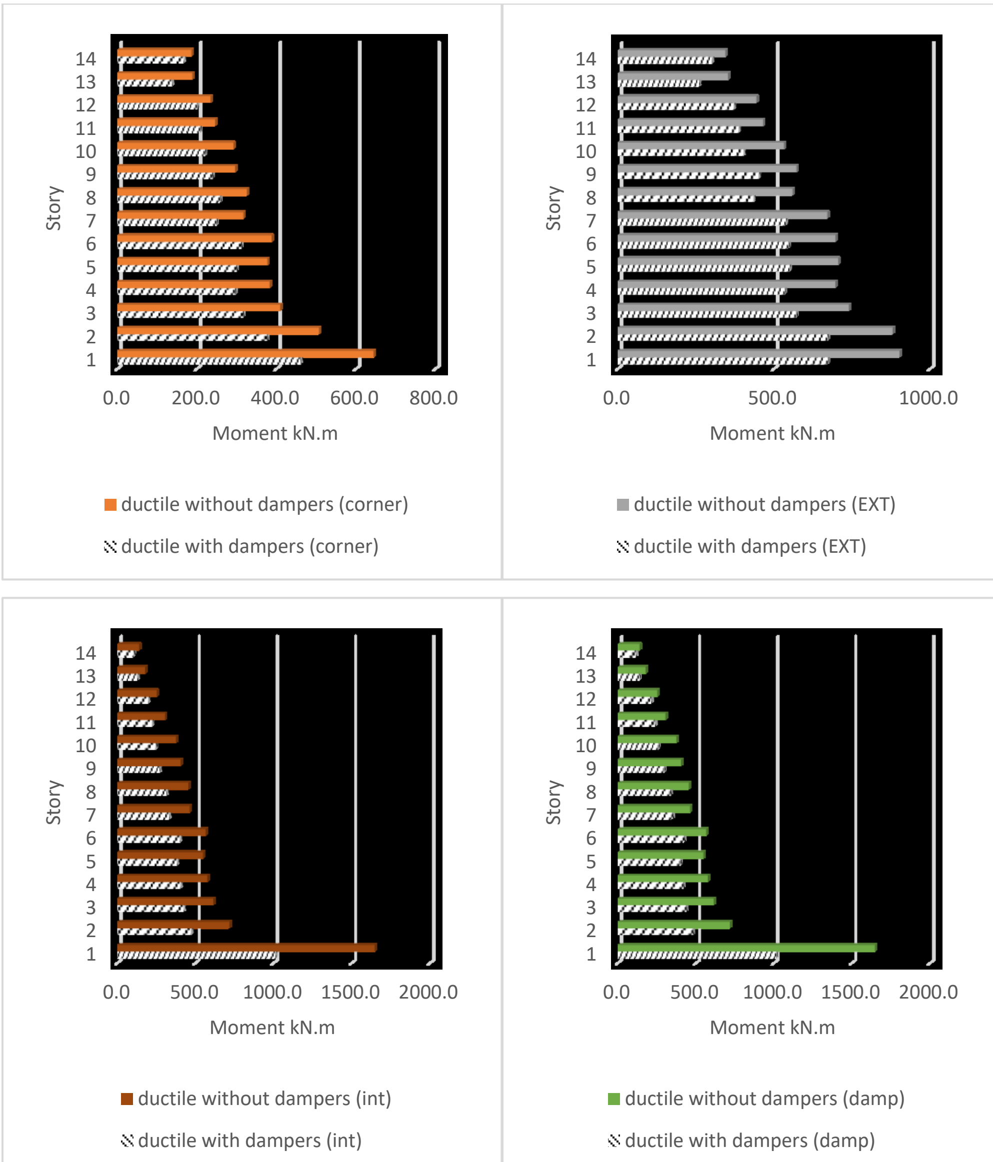


Figure 3-7 moment columns comparisons between model (DUC) & (DUC-D): (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a dampers.

The same conclusion was made as the two previous model and a final moment comparison was made at 25.0% difference between the model (DUC) and model (DUC-D).

Shear Force

As you can see on the curves below, the same behavior occurs as the previous model and was found that the difference in shear was about 22.9% on columns between the two ductile models.

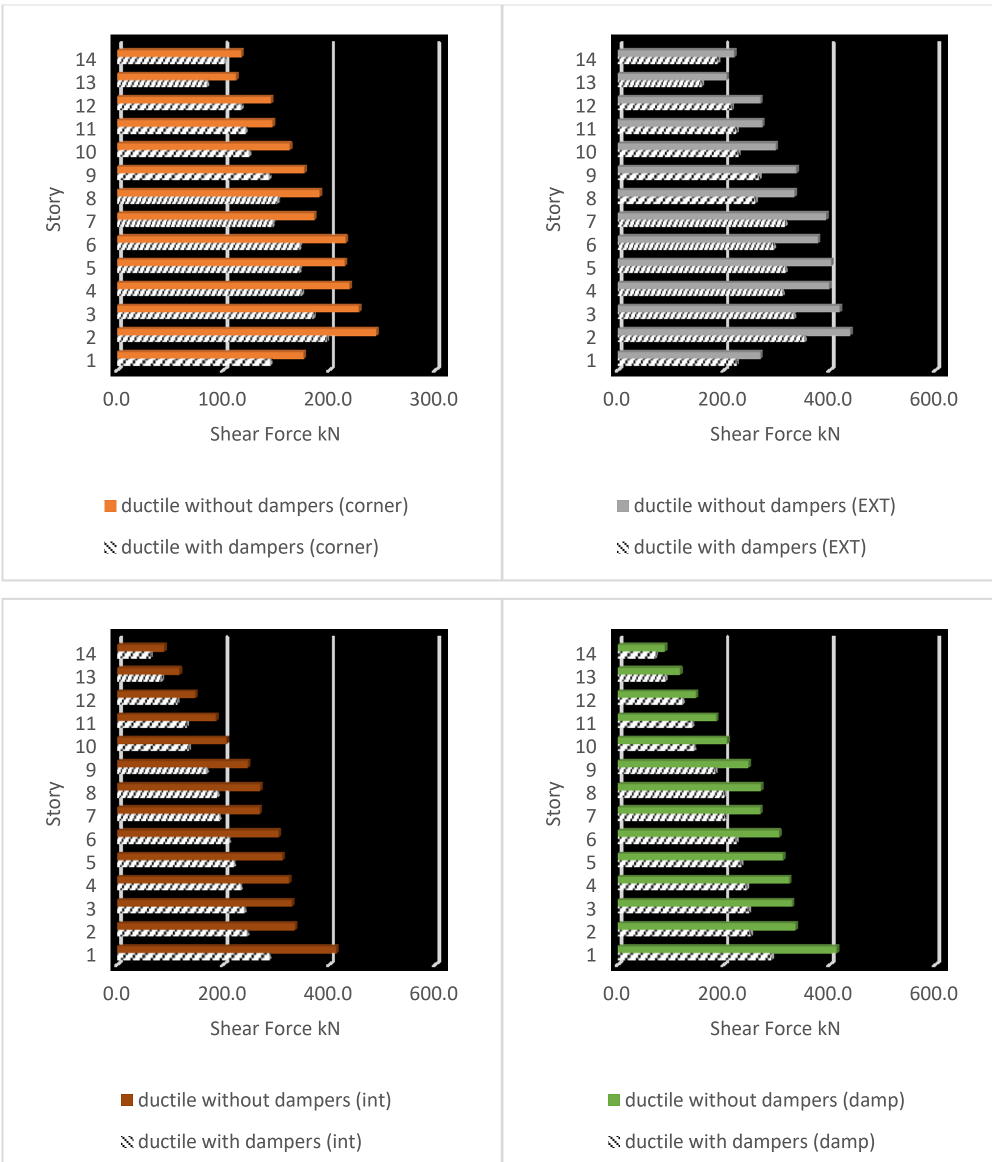


Figure 3-8 Shear Force columns comparisons between model (DUC) & (DUC-D): (a) between corner columns (b) between external columns (c) between internal columns (DUC) between internal columns connected to a damper

3.7 Economic Analysis

The purpose of this analysis is to show the difference in the quantity of material and the final total cost of materials required for each single design option. The comparison also takes into considerations the ratio of concrete/steel reinforcement details. Therefore, the increase in demand about low cost structure will be approached by showing a cost comparison in materials. In today's market, it is required to bring an economical approach to design a building, and it plays an important role in sustainable development.

Therefore, it can be shown that adding damper doesn't necessarily mean an increase in material cost but overall an increase in the actual building design seismic response.

Table 3-23 Steel Amount needed for each model design

Steel m^3	**EL**	**EL-D**	**MD**	**MD-D**	**DUC**	**DUC-D**
Column	61.63	56.09	16.17	12.56	20.78	14.63
Beam	145.44	136.65	42.61	40.81	31.22	26.02
Link	0.00	50.07	0.00	14.45	0.00	12.60
Total steel	207.06	238.35	64.96	67.35	52.00	53.56
	287%	345%	21%	26%	-3%	0%

Table 3-23 represents the amount of steel calculated for rebar and friction dampers links for each design. In the last row of the table the percentage difference in comparison to model (DUC): the ductile building, with the lowest amount of steel. It will be the main point of comparison, it can be noted that model (EL) & (EL-D) have more than 3 times the amount of steel and can be considered as a not economic option of design for building. Also designing a building as an elastic structure is rare because it requires stronger frame and are more expensive in general.

Table 3-24 Concrete Amount needed for each model design

Concrete m^3	**EL**	**EL-D**	**MD**	**MD-D**	**DUC**	**DUC-D**
Column	2208.56	1478.74	1304.44	891.45	1036.3	775.17
Beam	4307.68	3670.21	2518.64	2090.24	2423.0	2159.99
Floor	4716.79	4716.79	4670.54	4716.79	4716.8	4716.79
Total Concrete	11233.02	9865.73	8493.61	7698.48	8176.00	7651.95
	46.80%	28.93%	11.00%	0.61%	6.85%	0.00%

Table 3-24 represent the amount of concrete material for each structure. It can be noted that model (DUC-D) is the model that need the less amount of concrete.

Table 3-25 Steel cost needed for each model design

Steel ton^3	EL	EL-D	MD	MD-D	DUC	DUC-D
Column	483.88	440.42	126.97	98.62	163.16	114.90
Beam	1141.98	1072.98	334.57	320.44	245.14	204.31
Link	0.00	294.87	0.00	85.10	0.00	74.18
	1625.86	1808.26	461.54	504.16	408.30	393.39
Total Tons	313.29%	359.66%	17.32%	28.16%	3.79%	0.00%
USD$	$975,515	$ 1,031,881	$276,924	$287,176	$244,982	$222,682
% of Costs	31%	35%	14%	16%	13%	13%

Table 3-25 represents the final cost for steel amount using the material cost retrieved in American dollar in 2017 RSmeans catalogue [26].

The price of rebar and the price for the links aren't the same and it can be seen that Model (DUC-D) is cheaper then model (DUC) even though model (DUC) have a total smaller amount of steel into the structure.

Table 3-26 Concrete cost needed for each model

Concrete m^3	EL	EL-D	MD	MD-D	DUC	DUC-D
Column	2208.56	1478.74	1304.44	891.45	1036.26	775.17
Beam	4307.68	3670.21	2518.64	2090.24	2422.95	2159.99
Floor	4716.79	4716.79	4670.54	4716.79	4716.79	4716.79
Total m3	11233.02	9865.73	8493.61	7698.48	8176.00	7651.95
	46.80%	28.93%	11.00%	0.61%	6.85%	0.00%
% of Costs	69%	65%	82%	84%	87%	87%
USD$	$2,190,440	$1,923,817	$1,656,255	$1,501,203	$1,594,320	$1,492,

Table 3-26 represent the final cost for concrete amount using the material cost retrieve in American dollar in 2017 RSmeans catalogue [26].

Model (DUC-D): ductility with dampers is the cheapest cost in material in concrete.

Note that the row with "% of cost" for Table 3-25 & 3-26 represents the ratio of concrete/steel in the structure. It can be observed that model (DUC-D) has 13% of steel / 87% of concrete in comparison of model (EL), the most expensive model with a ratio of 31%/69%.

Table 3-27 Total Material cost

	EL	EL-D	MD	MD-D	DUC	DUC-D
Steel (USD$)	$975,515	$ 1,031,881	$276,924	$287,176	$244,982	$222,682
Concrete (USD$)	$2,190,440	$1,923,817	$1,656,255	$1,501,203	$1,594,320	$1,492,130
TOTAL	$3,165,955	$2,955,698	$1,933,179	$1,788,380	$1,839,302	$1,714,811
% of Costs	84.62%	72.36%	12.73%	4.29%	7.26%	0.00%
Difference of Costs	$1,451,144	$1,240,887	$218,368	$73,569	$124,491	$0

In summary, as shown on Table 3-27, model (DUC-D) is the most economical model in material cost. Also note that the model has dampers, adding dampers into the model reduce the material price of the structure. Dampers take about 30% of seismic load applied on the structure and consequently, the members of the structure have smaller moment/shear force applied on them and required smaller sections and less reinforcement.

Chapter 4 Seismic Response

This chapter contains the description of the dynamic analysis conducted. 2D models are used for those analyses as it is more efficient. The different cases or scenarios were used to perform a performance-based design analysis to concur the results obtained in the static analysis. At first a pushover analysis was conducted on each model to get a perception of the actual building strength. As a second analysis for the performance-bases, a dynamic non-linear analysis is conducted in each building. The analysis conducted using ETABS is a non-linear direct time history analysis. Ten ground motion were selected and are described in Chapter 2, as time history matched with Vancouver's spectrum.

4.1 Pushover analysis

This analysis consists of a static non-linear analysis of a specific building. It takes into consideration the conventional displacement control method and the elastic stage of the structure under loads that horizontally "pushes" the structure to get a certain target displacement. The pushover analysis is based on the code FEMA-440 [8]. The structure is "pushed" by an earthquake load applied horizontally to the structure throughout its height to get the target displacement. By using this method, the behavior of the post-yield range can be observed. To get more accurate results, plastic hinges were defined based on the hand-calculation as per FEMA guidelines [7, 8, 9], and subsequently applied to the structure on the beam edges. The column hinges were used as predefined by the software used (i.e., ETABS), since the structure was designed under the weak beam-strong columns concept.

4.1.1 Elastic models with and without dampers (EL) & (EL-D)

Those structures are designed with a ductility associated full elasticity, and the pushover can be used as a tool to measure the potential of ductility of the structure. The results concur with the design attribute of full elasticity into the building, the curve shows that the structure stays into the elastic zone. The pushover results for the elastic model (EL) can be observed in Figure 4-1 below, the structure stays in the elastic zone with a base shear of 102 100 kN. It can be noticed that model (EL-D) with dampers is stiffer by observing Figure 4-2 & 4-3, with a similar design base shear as model (EL).

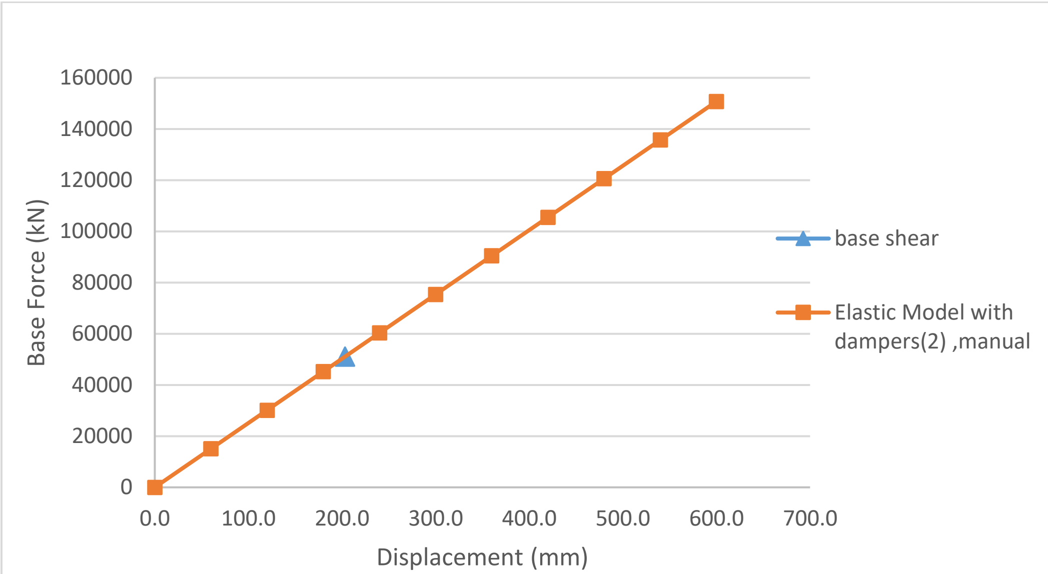


Figure 4-1 Pushover curve for Elastic building (EL)

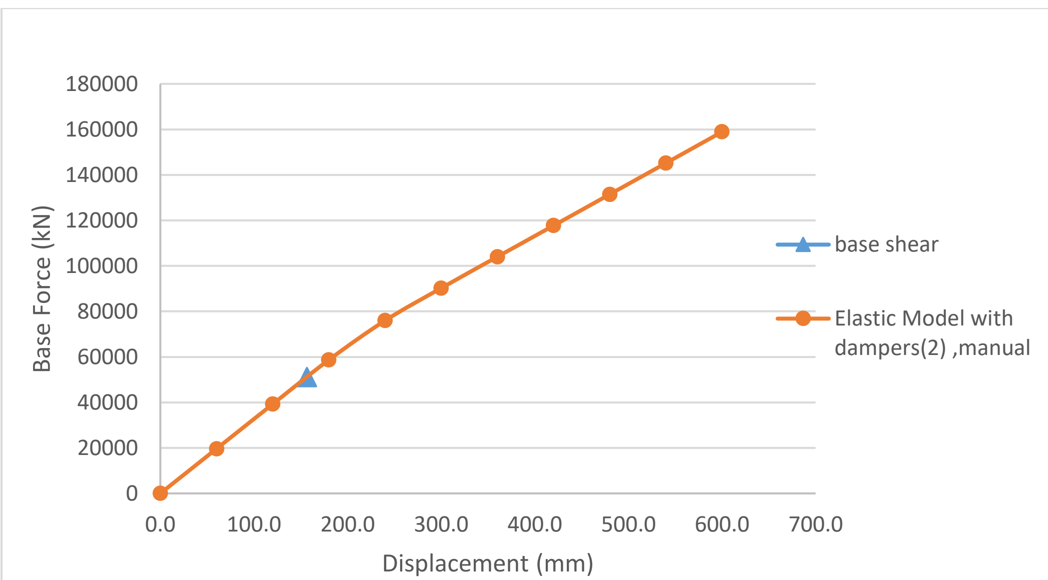


Figure 4-2 Pushover curve for Elastic with dampers building (EL-D)

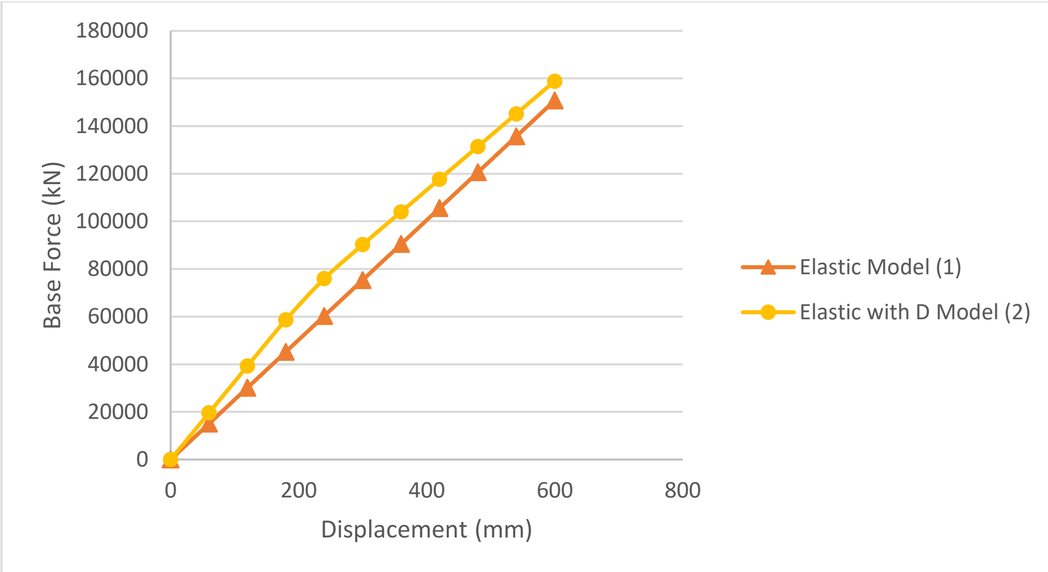


Figure 4-3 Pushover curve for Elastic building (EL) & (EL-D)

4.1.2 Moderately-ductile models with and without dampers (MD) & (MD-D)

The pushover results for the moderately-ductile model (MD) can be observed in Figure 4-4, where the structure stays in the elastic zone until a base shear level of nearly 8,950 kN. The building was designed with the base shear of $V_d = 8543.66$ kN. It can be noted that model (MD-D) with dampers is stiffer by observing Figures 4-5 & 4-6, the structure stays into the elastic zone until an applied base shear of nearly 10700 kN, with a similar design base shear as model (MD). For both model, the maximum displacement for the pushover curve occur around 600 mm.

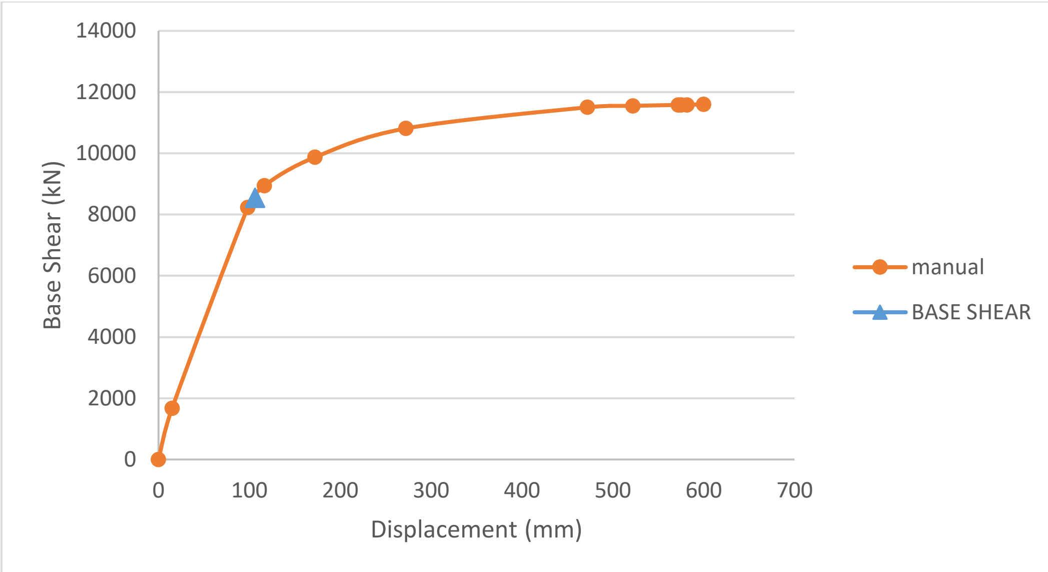


Figure 4-4 Push-Over curve for Moderately-Ductile building (MD)

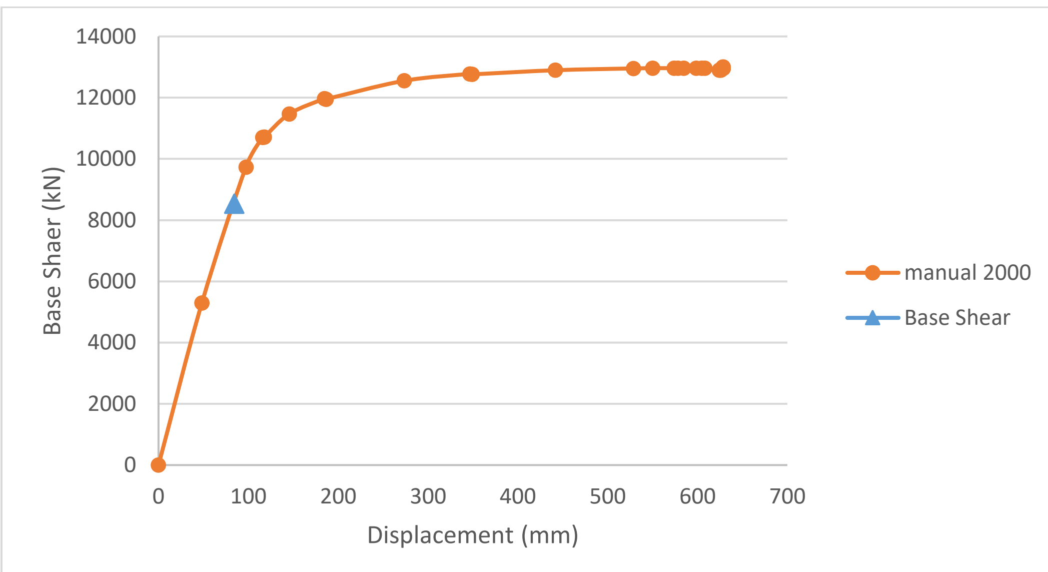


Figure 4-5 Push-Over curve for Moderately-Ductile with dampers building (MD-D)

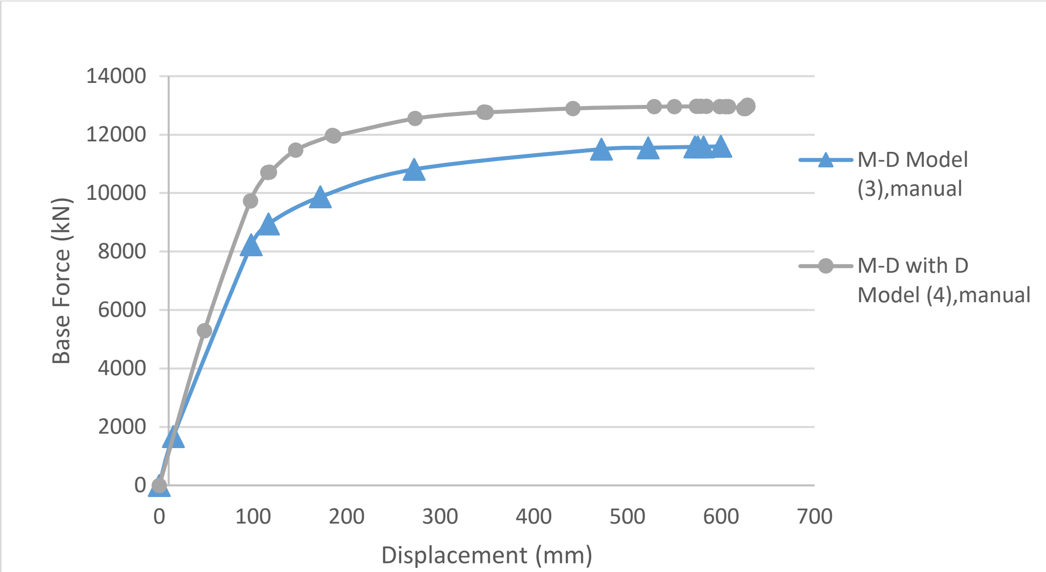


Figure 4-6 Pushover curve for M-D building (MD) & (MD-D)

4.1.3 Ductile models with and without dampers (DUC) & (DUC-D)

The push-over results for the ductile model (DUC) can be observed in Figure 4-7 below, the structure stays in the elastic zone until a base shear of nearly 5,300 kN. The building was designed with an initial base shear V_d = 4286 kN. It can be noticed that model (DUC-D) with dampers is stiffer by observing its push-over curve, the structure stays into the elastic zone until an applied base shear of nearly 6,400 kN, with a similar design base shear as model (DUC). In Figure 4-9, both curves overstep each other at some point; however, it can be noticed that the structure (DUC-D) stays in the plastic zone under a higher base shear, and with a displacement, or nearly 800 mm.

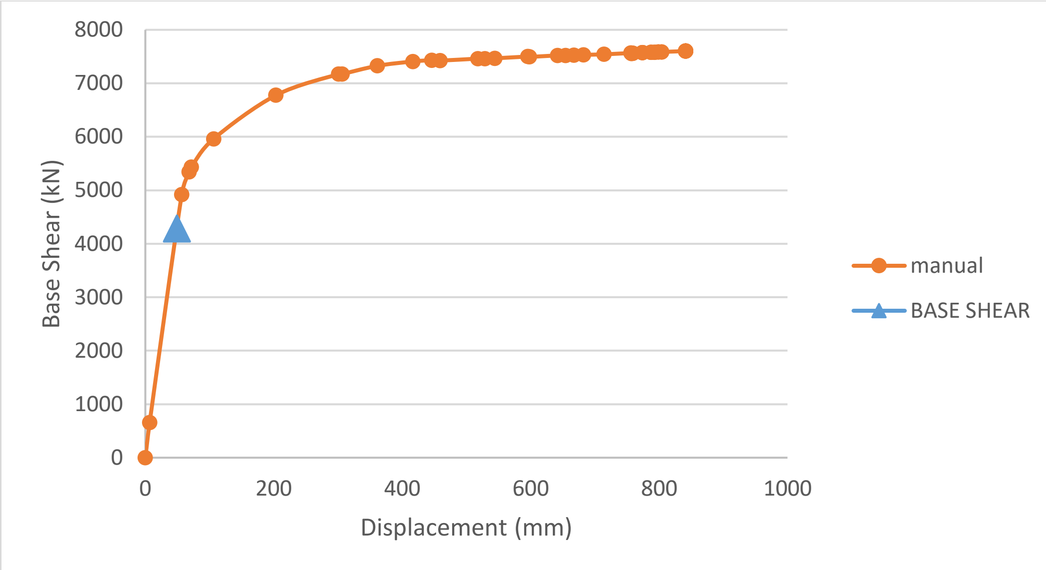


Figure 4-7 Pushover curve for Ductile building (DUC)

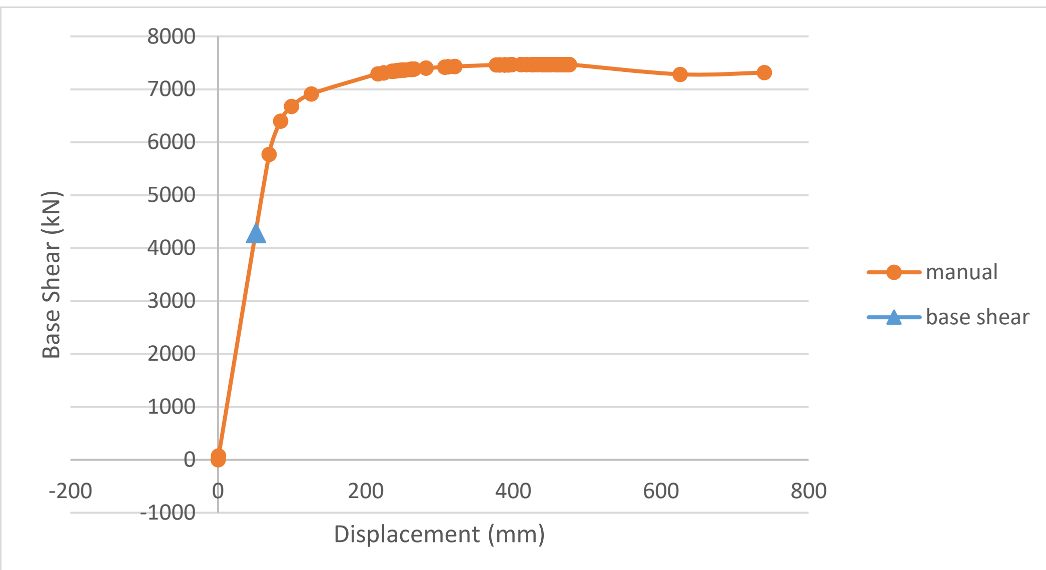


Figure 4-8 Pushover curve for ductile with damper building (DUC-D)

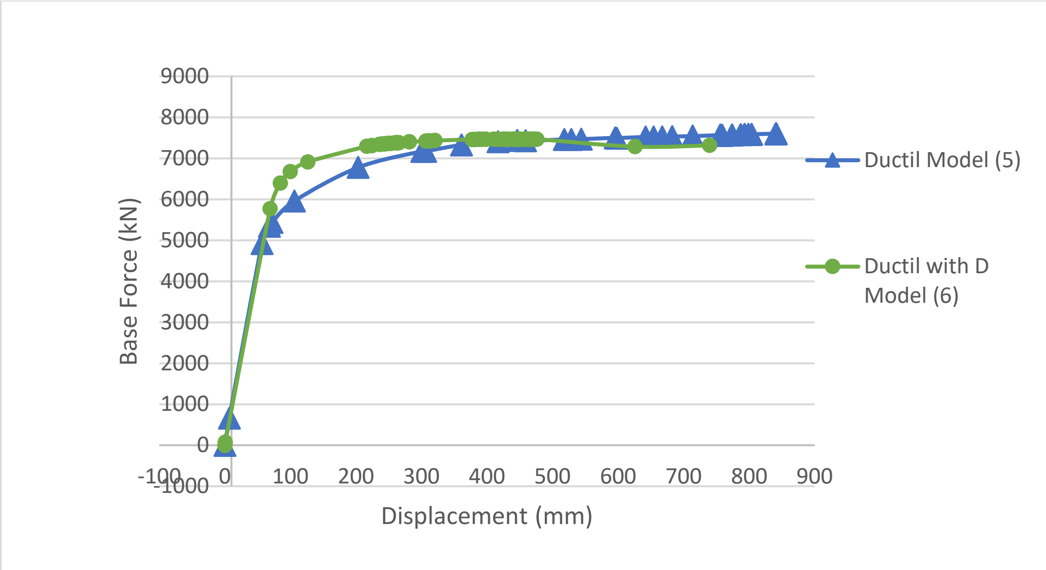


Figure 4-9 Pushover curve for ductile buildings (DUC) & (DUC-D)

4.2 Non-linear Dynamic Analysis

A 2D fast non-linear time-history analysis is conducted to be able to get another approach of the building's real response. As the FEMA 356; 9.3.5.2 Nonlinear Dynamic Procedure [7] code mention, no additional global structural damping should be added to the structure when using non-linear time-history analysis for passive energy devices as friction dampers.

4.2.1 Elastic frame models with and without dampers (EL) & (EL-D)

The time-history analysis was used to determine the drift on the structures. Figures 4-10 & 4-12 shows, respectively, the inter story drift for elastic frame without and with friction dampers. Figure 4-11 & 4-13 shows, respectively, the mean values, standard deviation and "mean value + standard deviation" of inter story drift ratios of models (EL) & (EL-D). Figure 4-14 displays the sum of the standard deviation and the mean values for both model and even though the sections were reduced of about 7.1% for the structure with dampers (EL-D) it has less drift.

It can be observed that the maximum drift occurs at 46.5m and 39.5 m height respectively for model (EL) & (EL-D). For the model (EL), the maximum inter-story is of 1.40%, and for the model (EL-D) is 1.13%.

Both models are in the range of the "Life safety" response of the structure defined in NBCC 2015 [18].

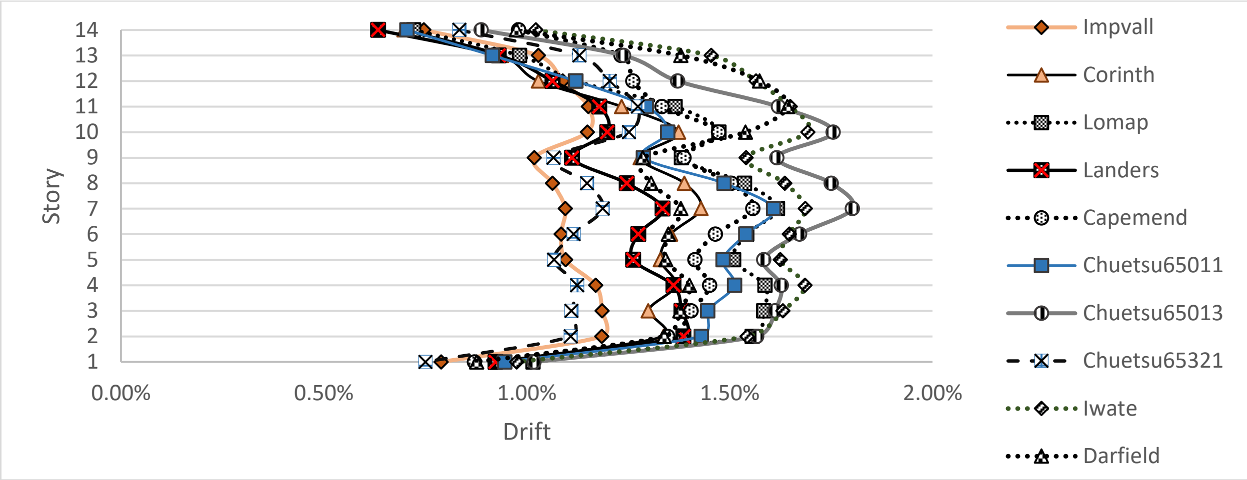


Figure 4-10 Time History drift for elastic model (EL)

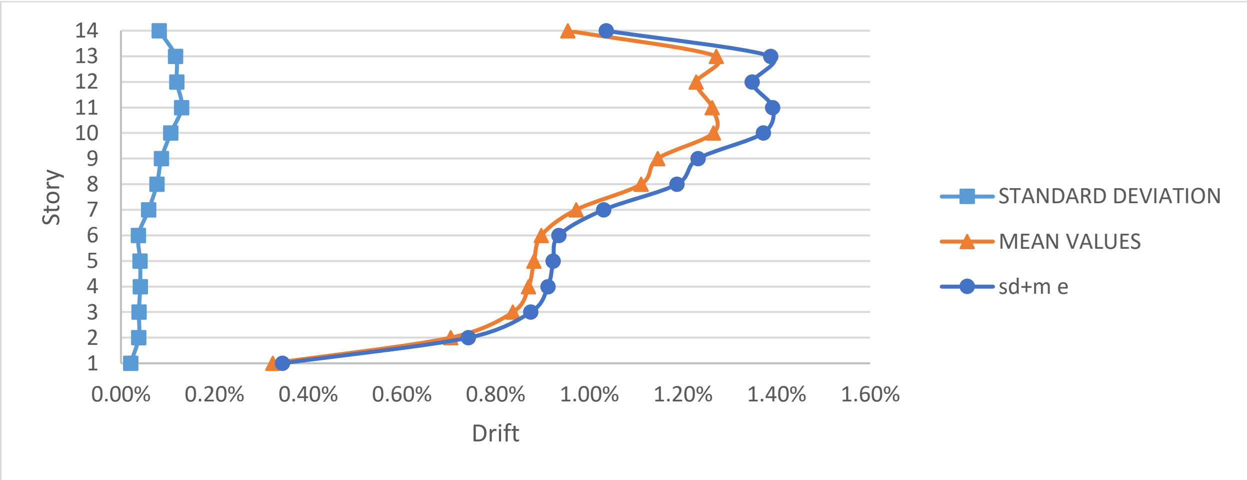


Figure 4-11 Standard deviation, mean values and sum for the Time History drift for elastic model (EL)

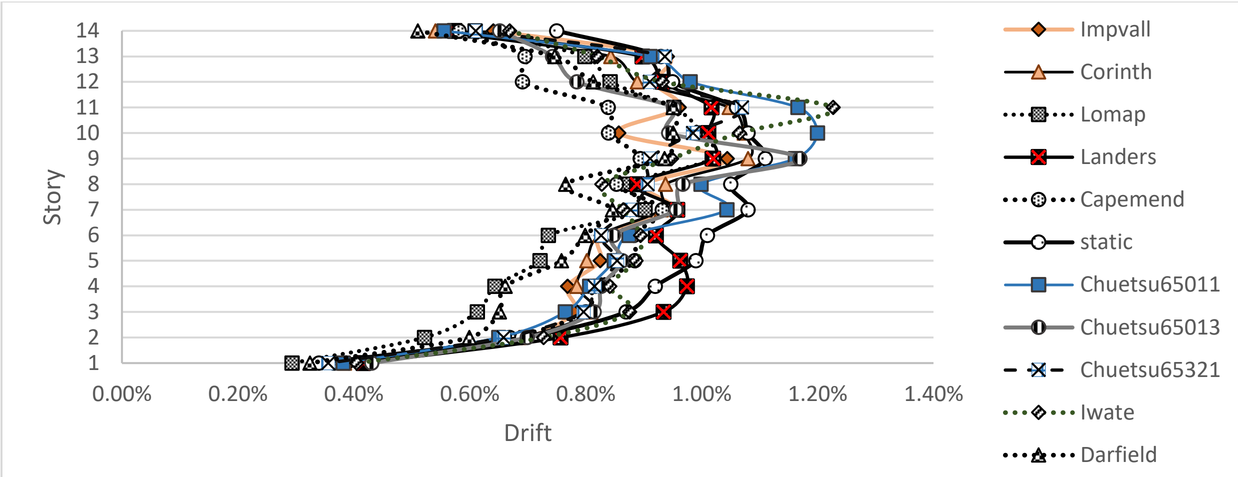


Figure 4-12 Time History drift for elastic with dampers model (EL-D)

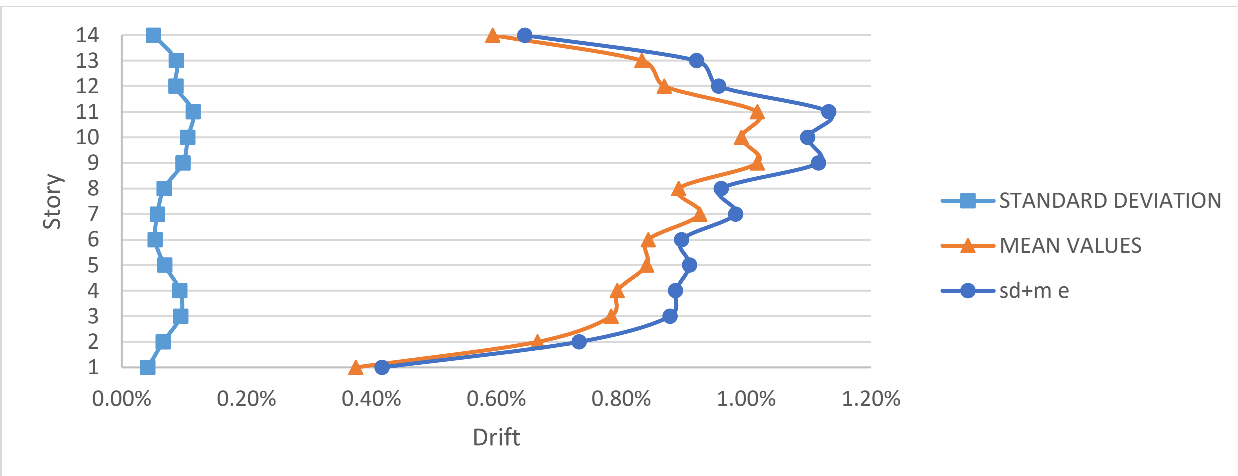


Figure 4-13 Standard deviation, mean values and sum for the Time History drift for elastic model with dampers (EL-D)

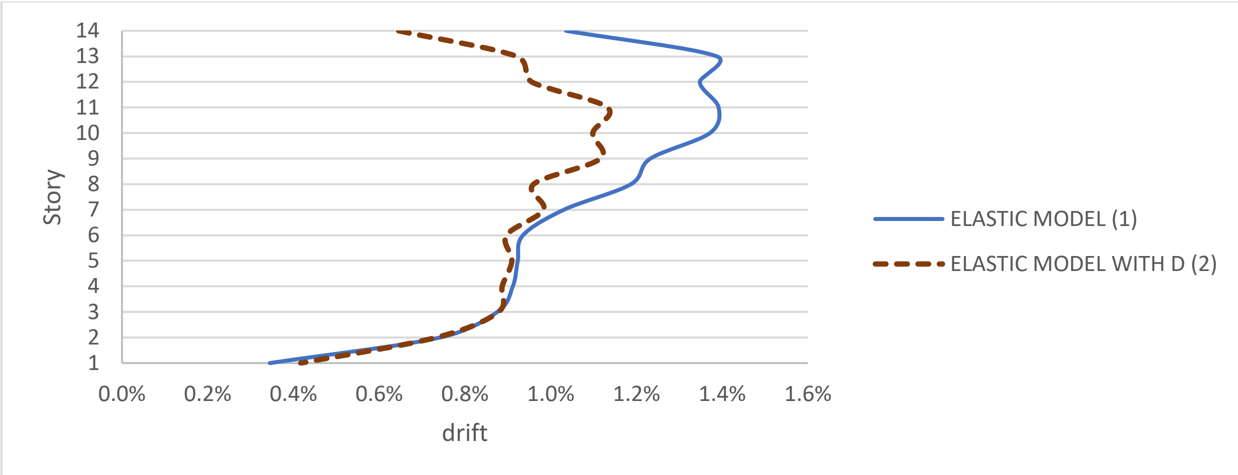


Figure 4-14 Standard deviation + Mean value Drift for time History analysis model (EL) & (EL-D)

4.2.2 Moderately-ductile models (MD) & (MD-D)

Figure 4-15 & 4-17 show, respectively, the inter story drift for moderately-ductile frame without and with friction dampers. Figure 4-16 & 4-18 shows, respectively, the mean values, standard deviation and "mean value + standard deviation" of inter story drift ratios of models (MD) & (MD-D). Figure 4-19 displays the sum of the standard deviation and the mean values for both model and even though the sections were reduced of about 8.1% for the structure with dampers (MD-D) it has less drift.

It can be observed that the maximum drift occurs at 36 m and 18.5 m height respectively for model (MD) & (MD-D). For the model (MD), the maximum inter-story is of 1.94%, and for the model (MD-D) is 1.59%. Both models are in the range of the "Life safety" response of the structure defined in NBCC 2015 [18].

The same conclusion can be made as the elastic models results.

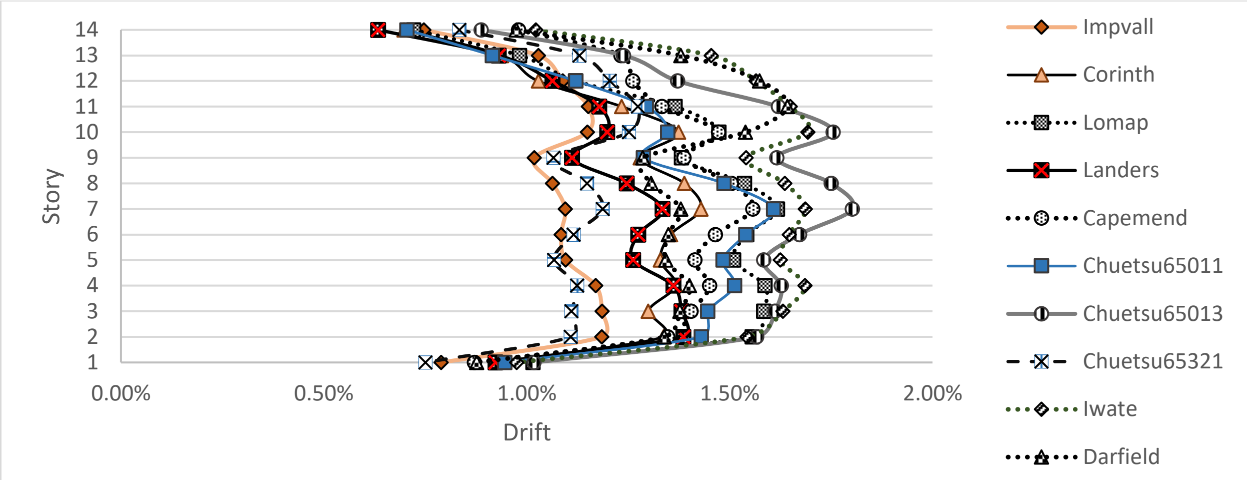


Figure 4-15 Time History drift for moderately- ductile model (MD)

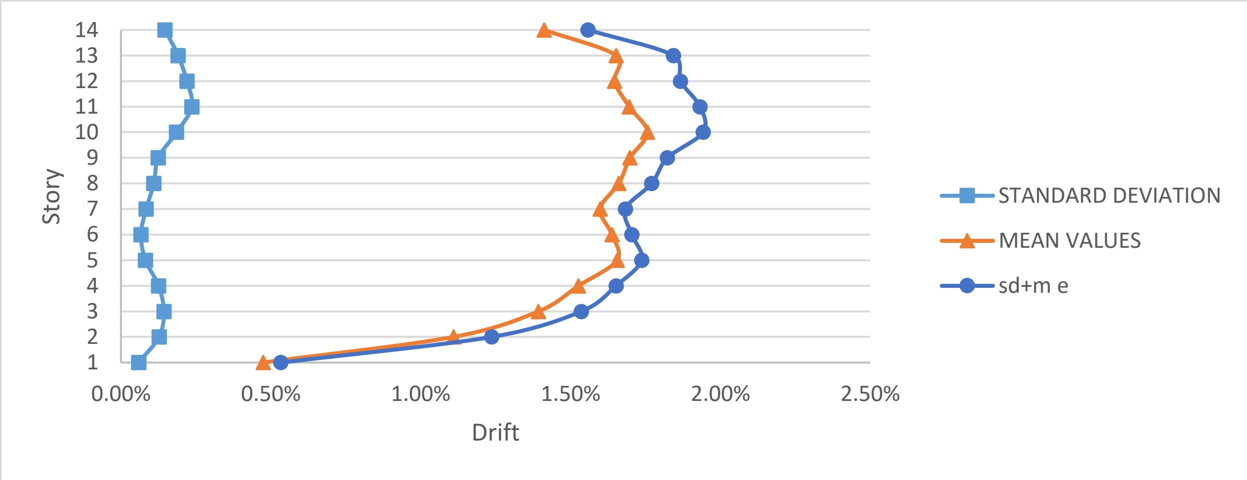


Figure 4-16 Standard deviation, mean values and sum for the Time History drift for moderately-ductile model (MD)

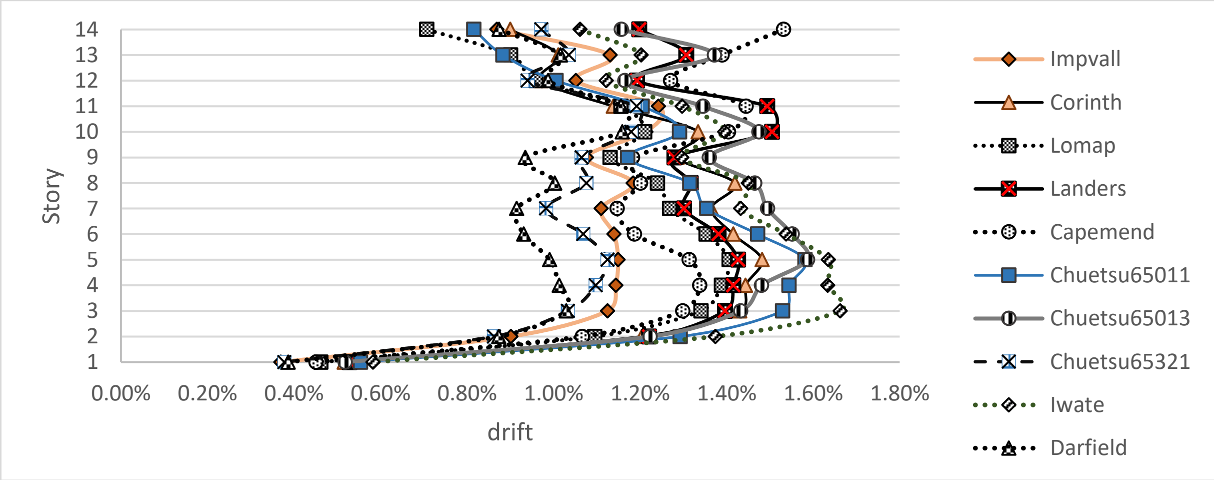


Figure 4-17 Time History drift for moderately- ductile model with dampers (MD-D)

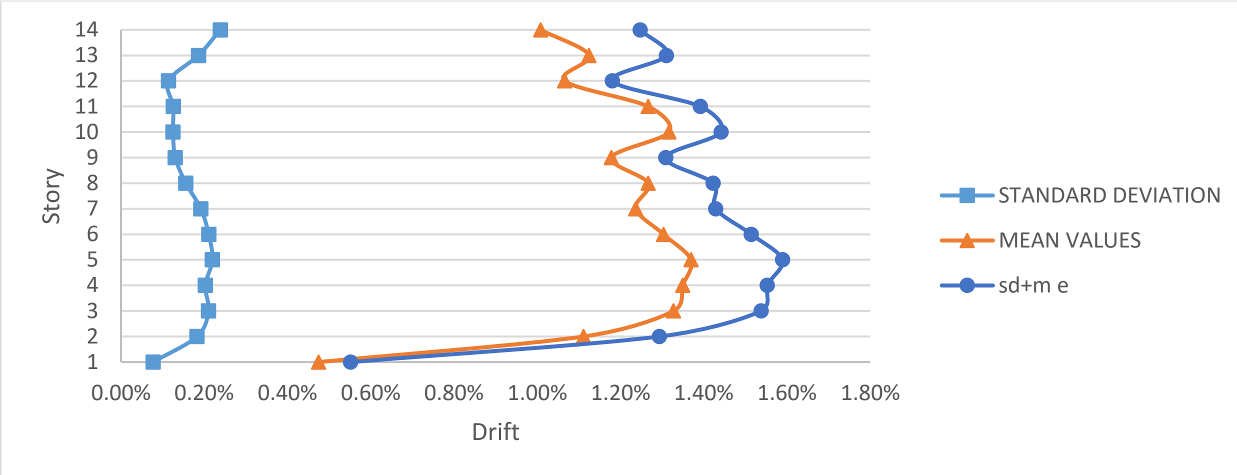


Figure 4-18 Standard deviation, mean values and sum for the Time History drift for moderately-ductile model with dampers (MD-D)

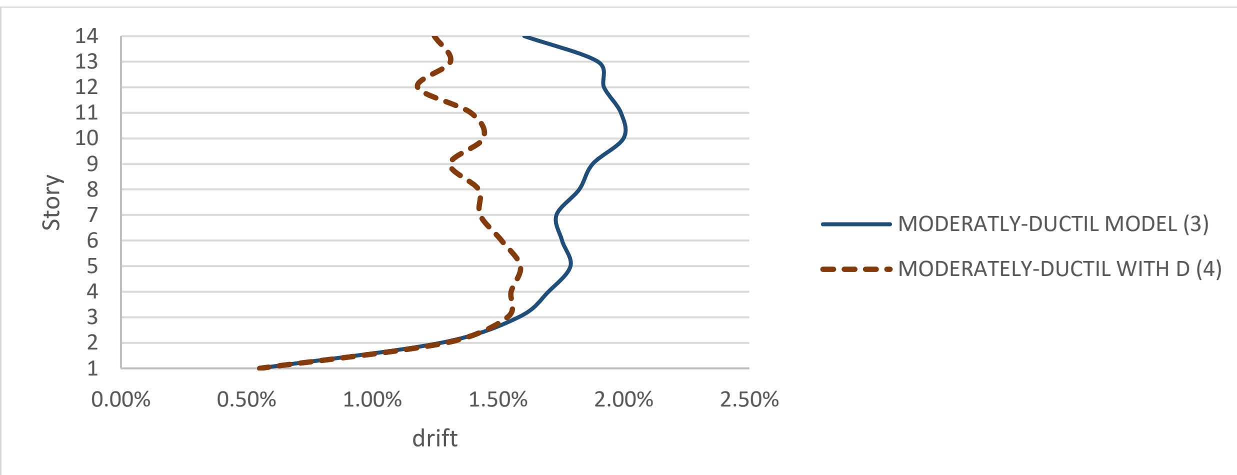


Figure 4-19 Standard deviation + Mean value Drift for time History analysis model (MD) & (MD-D)

4.2.3 Ductile model (DUC) & (DUC-D)

Figure 4-20 & 4-22 show, respectively, the inter story drift for ductile frame without and with friction dampers. Figure 4-21 & 4-23 show, respectively, the mean values, standard deviation and "mean value + standard deviation" of inter story drift ratios of models (DUC) & (DUC-D). Figure 4-24 displays the sum of the standard deviation and the mean values for both model and even though the sections were reduced of about 7.3% for the structure with dampers (DUC-D) it has less drift.

It can be observed that the maximum drift happens at 15 m and 39.5 m height, respectively, for model (DUC) & (DUC-D). For the model (DUC), the maximum inter-story is of 2.00%, and for the model (DUC-D) is 1.89%. Both models are in the range of the “Life safety” response of the structure defined in NBCC 2015 [18].

The same conclusion can be made as the elastic models results.

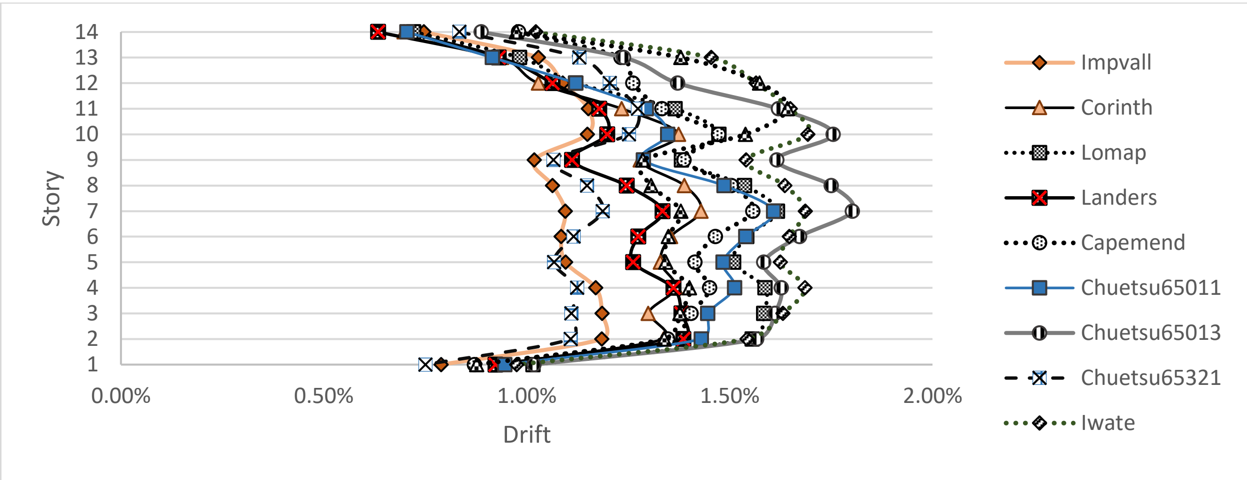


Figure 4-20 Time History drift for ductile model (DUC)

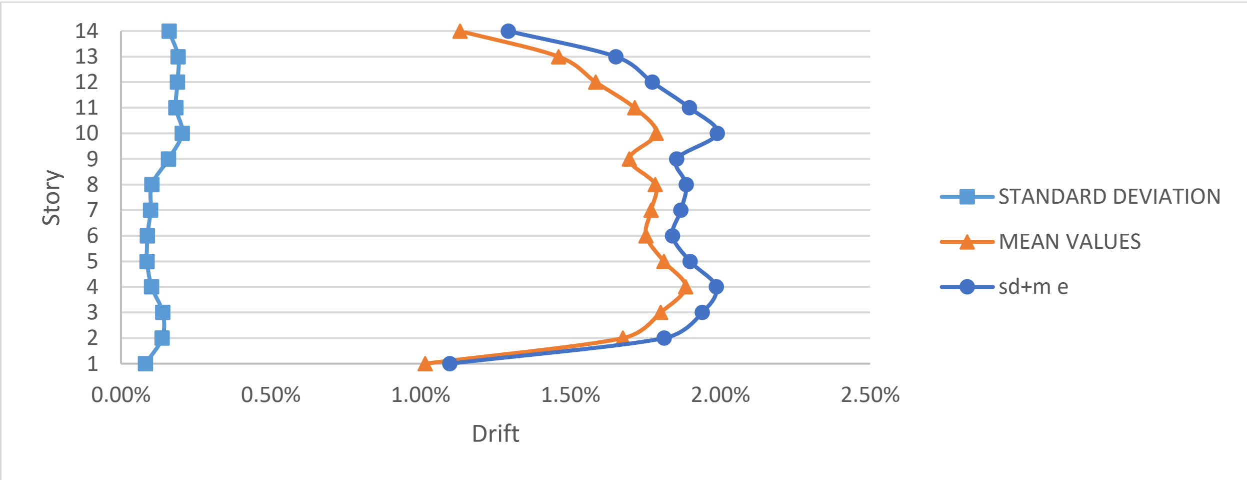


Figure 4-21 Standard deviation, mean values and sum for the Time History drift for ductile model (DUC)

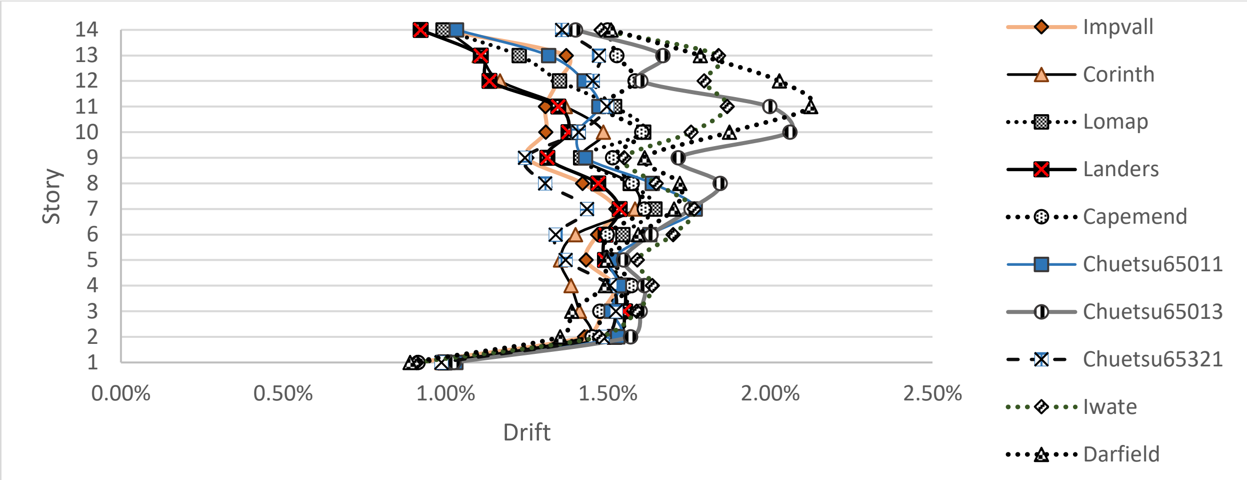


Figure 4-22 Time History drift for ductile model with dampers (DUC-D)

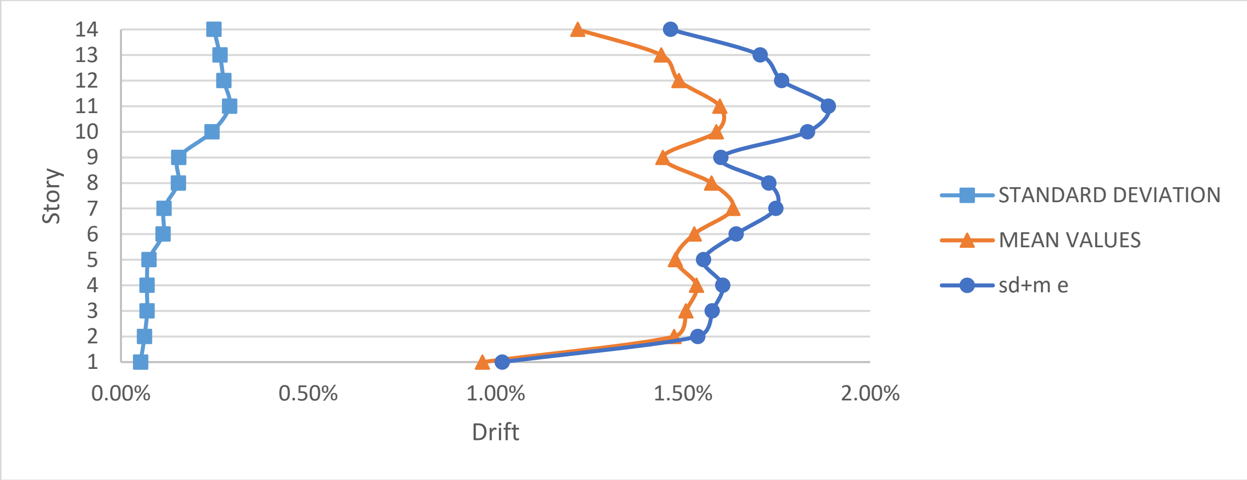


Figure 4-23 Standard deviation, mean values and sum for the Time History drift for ductile model with dampers (DUC-D)

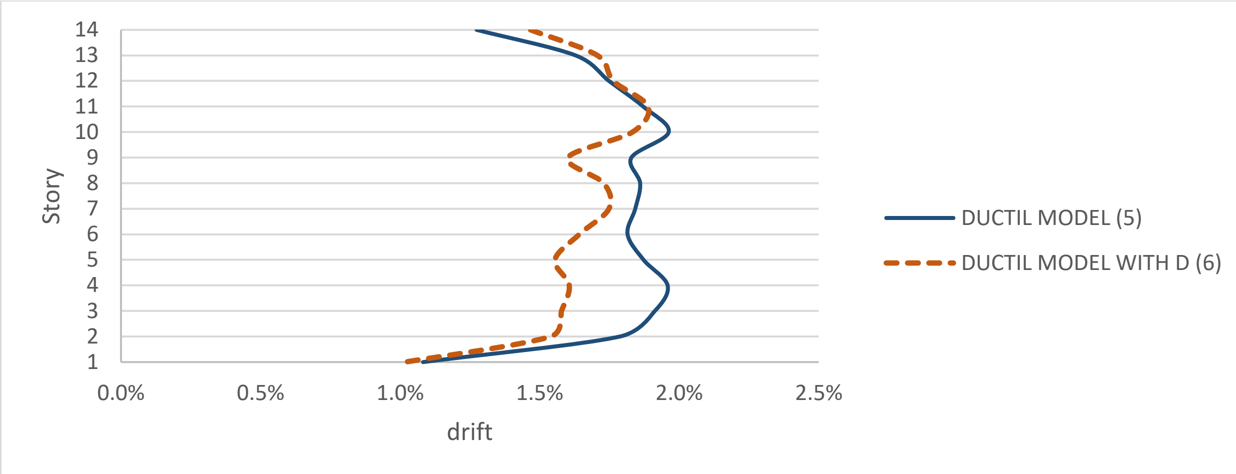


Figure 4-24 Standard deviation + Mean value Drift for time History analysis model (DUC) & (DUC-D)

In summary, the inter-story drift values are smaller between the same models with dampers. The buildings with dampers are re-designed after observing the benefit of dampers in the reduction of moment and shear. By reducing section, the building became less expensive with bigger space for occupancy and stay in the "life safety zone" as the structure with same ductility due to the slippage of dampers into the structure. It can be observed that structure with smaller section and with dampers have smaller drift due to the slippage of the dampers that absolves energy. The push-over curve shows that buildings with dampers have higher elastic stiffness. The push-over curve shows that the dampers' slipping is consistent in the elastic range of the structure.

By foreword building with dampers, even though they have smaller sections, they have a stronger push-over curve and smaller inter-story drift, than the similar ductility building without dampers. The seismic behavior concord with the static analysis by displaying the benefits of dampers into the design of buildings.

4.3 Displacement level at dampers

Friction dampers in this research where designed to slip in the direction of the dampers, that are placed in the structure is in two directions U1 (y or x direction) and U2 (z direction). In Tables 4-1,4-2 and 4-3, the final displacement level at the critical dampers at each floor are shown in the three different ductility cases, (E-D, MD-D, DUC-D), respectively. The final damper movement in the damper direction is also calculated to obtain the approximated slip length that each damper would require when designed. Time-history non-linear analysis was used to calculate the damper displacements as shown in Tables 4-1, 4-2 and 4-3. Only the critical cases of the 10 ground-motions used here is shown as the longest displacement calculated during the analysis. To be conservator and because in numerous previous research it was shown that ± 25% of slip force can differentiate over time without influencing the overall action on the structure. It would be recommended to take 1.25 times the slip calculated as the used slip length for the design of a friction damper.

Table 4-1 Displacement level at dampers for model (EL-D): elastic model with dampers

Story	**U1 (UY) mm**	**U2 (UZ) mm**	**$U_{dampers}$ mm**	**slip length recommended**
14	15	23	27	35
13	20	22	30	40
12	20	25	32	40
11	26	26	36	45
10	25	30	39	50
9	25	24	34	45
8	19	28	33	45
7	20	23	31	40
6	19	29	35	45
5	21	28	35	45
4	22	37	43	55
3	22	38	44	55
2	19	38	42	55
1	14	32	35	45

Table 4-2 Displacement level at dampers for model (MD-D): moderately-ductile model with dampers

Story	U1 (UY) mm	U2 (UZ) mm	$U_{dampers}$ mm	slip length recommended
14	35	60	73	90
13	36	68	79	100
12	32	48	60	75
11	36	60	72	90
10	39	61	79	100
9	33	54	63	80
8	35	55	65	80
7	34	60	70	90
6	38	62	76	95
5	36	72	83	105
4	41	66	87	110
3	35	80	90	115
2	35	67	85	110
1	16	54	57	70

Table 4-3 Displacement level at dampers for model (DUC-D): Ductile model with dampers

Story	U1 (UY) mm	U2 (UZ) mm	$U_{dampers}$ mm	slip length recommended
14	44	85	96	120
13	51	95	121	150
12	49	84	121	150
11	61	101	118	150
10	48	76	99	125
9	45	85	101	125

8	49	86	99	125
7	47	88	100	125
6	41	69	89	110
5	40	75	86	110
4	43	77	88	110
3	41	76	88	110
2	41	72	83	105
1	33	20	84	105

Chapter 5 Conclusions

5.1 Summary

This study focuses on the impact of friction dampers into the design stage of a building. This research is conducted by taking into consideration; the economic, the building ductility, seismic response and the better space occupancy. For this study, three models are designed with different ductility levels (elastic, moderately-ductile and ductile). Afterwards, those three buildings are redesigned by including friction dampers on 8 frames, of each floor (4 on each directions). Optimization on the section is made with an exact same base core for all 6-final building. The 6 structures are designed by using ETABS [2, 3] and compared to hand calculation to increase the accuracy of the results. After the buildings are designed with proper section and with and without dampers, a static analysis was performed to compare the impact of shear and moment on the columns. The sections of the models with dampers were greatly reduced. The moment and shear results on columns show that the presence of dampers diminish the moment and shear force apply on columns. Also, a simple cost analysis of material cost was made, and it was shown that the cost between a model with and without dampers is about 7% less expensive due to the optimization that could be made with the impact of dampers on moment shears of the structures.

Secondly, the 2D models are made and used to conduct a performance-oriented design analysis of the 6 structures. A push-over analysis is conducted on each building, and it was concluded that the structure with dampers has higher base shear with similar displacement as the building without dampers. Both structure had their design base shear into the yield zone. Hand-calculated plastic hinges were used in the building models to get more accurate results. Push-over is conducted using the full earthquake load applied on the structure. Nest, a non-linear time-history analysis was performed using 10 different ground motions scaled to the response spectrum of Vancouver. The final results of the time history analyses show a similar drift between the model with and without dampers. However, the building with dampers was previously shown to have more space, less material, less expensive, less shear, less moment into the structure and a stronger push-over response. The final results of the time history analyses show smaller drift for structure with dampers than the one without dampers.

The building with dampers was shown in this research to have more space, less material, less expensive, less shear, less moment into the structure, a stronger pushover curve that demonstrate that the building stays into the elastic zone under stronger forces and smaller inter-story drift that establish that the building with dampers have stronger performance for a lower cost.

5.2 Conclusion and recommendations

This research provided some conclusions about the impact of dampers into the design process of building. Four main analyses were performed during this study and the following conclusions are made. At the end of the research the determination of the most intelligent choice of the structure that should be selected as an interesting cost-performance-ratability building for further construction will be made.

The following are the conclusions that were determined by this study:

1. Dampers have a clear impact into the shear force and moment applied on the columns and beams of a structure. They are greatly reduced by the approximate number of dampers shear force taken by them. As for this research, dampers were designed to take between 25-35% of the shear. Table 5-1 shows the actual moment and shear difference average on columns for same ductility structure with and without dampers.

Table 5-1 Moment and shear difference average on columns for same ductility structure with and without dampers

	Elastic (EL) & (EL-D)	Moderately-Ductile (MD) & (MD-D)	Ductile (DUC) & (DUC-D)
Moments	41.1%	27.6%	25.0%
Shear	36.6%	22.8%	22.9%

The results are conformed to the dampers assumed parameter.

2. The cost analysis of total material need for designing the structures show that buildings including dampers are less expensive. Table 5-2 show the difference in cost of materials need it between similar ductility building with and without dampers.

Table 5-2 Difference in cost of materials need it between similar ductility building with and without dampers

	Elastic (EL) & (EL-D)	Moderately-Ductile (MD) & (MD-D)	Ductile (DUC) & (DUC-D)
Difference of Costs in %	7.1%	8.1%	7.3%

The less expensive structure is the ductile with dampers model (DUC-D) at $1,492,130.00, followed by the moderately ductile with dampers model (MD-D) at $1,501,203.00.

3. The push-over analysis shows that the structures with dampers has stronger base shear for similar displacement of the structure without dampers.
4. The fast-non-linear time history show that structure with dampers have less inter-story drift then the similar ductility building without dampers. In Table 5-3, it is shown that the average difference in inter-story drift of similar ductility level in building without and without dampers.

Table 5-3 Average difference in inter-story drifts for similar ductility building with and without dampers

	Elastic (EL) & (EL-D)	Moderately-Ductile (MD) & (MD-D)	Ductile (DUC) & (DUC-D)
Difference of drift (average) in %	11.4%	8.83%	6.51%

5. Fast-non-linear time history analyses of the models with dampers (E-D, MD-D, DUC-D) also permitted to determine the actual slip length of the dampers that can occur. A design slip length at each floor for the models with dampers was found and recommended.

In conclusion, the time history analysis shows that the structure with same ductility have smaller drift when they have dampers and are also more economic, with smaller section and have stronger push-over response.

It can also be observed that dampers influence the structure by taking some shear and moment that by consequence allows the structure to have smaller section and less reinforcement without influence the performance-based design. It can even be noticed that structure with dampers have stronger performance-based design.

The most economic building with the stronger pushover and smaller drift is found to be the ductile model with damper. Nevertheless, the property of ductile structures makes it the least resilient structure as it may undergo epos-earthquake damage. For a ductile structure sustaining damage may be expensive to repair. However, if a moderately ductile building suffers an event, it will stay into a life safety level and they have a greater chance to be rehabilitated. Resilient structures are designed to be able to have reconstruction after a damaging event. Moderately-ductile structures with damper will potentially offer this option.

In conclusion, the moderately-ductile building with damper (MD-D), will be the most adequate design to be used as an engineer. The cost difference between the ductile structure and moderately-ductile structure with dampers can be considered insignificant in comparison to the reconstruction cost or reparation cost that could occur at an event. Further research has to be done on this subject, the resilience of the structure would need to be taken into consideration and study, in site and real life study of the building would need to be conducted to get a more accurate observation of the assumption that have been made and study in this research. Now-a-days, no code for friction dampers is available to guide the design concrete structures with damoers, and it needs to be detailed so engineers can have a reference code and be able to use those new techniques. Finally, a comparison between other types of dampers would need to be done to observe the prose and cons of using friction dampers as an energy dissipation device into the design stage to increase the seismic strength and performance, It is also important to optimize the overall structural members and cost.

Chapter 6 References

1. Baker, J. (2011). Conditional Mean Spectrum: Tool for Ground-Motion Selection. *Journal of Structural Engineering*, *137*(3), 322-331. http://dx.doi.org/10.1061/(asce)st.1943-541x.0000215

2. *Concrete Frame Design Manual CSA A23.3-14 for ETABS® 2016*. (2015). United States of America.

3. CAC. (2017). *CONCRETE DESIGN HANDBOOK* (4th Ed.). Cement Association of Canada.

4. Chen, W., & Scawthorn, C. (2003). *Earthquake engineering handbook* (chapter 6). Boca Raton, FL: CRC Press.

5. Dalal, S., Dalal, P., & Desai, A. (2017). Effect of Increasing Ductility Factors on the Performance of a Steel Moment Resisting Frame Designed by the Performance Based Plastic Design Method attuned with Indian Code of Practice. *Procedia Engineering*, *173*, 1862-1869. http://dx.doi.org/10.1016/j.proeng.2016.12.238

6. Eslami, A., & Ronagh, H. (2012). Effect of elaborate plastic hinge definition on the pushover analysis of reinforced concrete buildings. *The Structural Design of Tall and Special Buildings*, *23*(4), 254-271. http://dx.doi.org/10.1002/tal.1035\

7. FEMA 356. (2000) *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, ASCE for the Federal Emergency Management Agency, Washington, D.C., November 2000.

8. *FEMA 440. (2005). Improvement of nonlinear static seismic analysis procedures*. ASCE for the Federal Emergency Management Agency, Washington, D.C.

9. FEMA 454. (2006). *Designing for earthquakes*. Books Express Publishing.

10. Guan, X., & Ou, J. (2008). *Study of Smart Friction Damper Based on Smart Micro-Drive Actuator | Earth & Space 2008*. *Ascelibrary.org*. Retrieved from http://ascelibrary.org/doi/pdf/10.1061/40988(323)178

11. Heysami, A. (2015). Types of Dampers and their Seismic Performance during an Earthquake. *Current World Environment*, *10*(Special-Issue1), 1002-1015. http://dx.doi.org/10.12944/cwe.10.special-issue1.119

12. Jackson, M., & Scott, D. (2010). *Increasing Efficiency in Tall Buildings by Damping Structures Congress 2010*. *Ascelibrary.org*. Retrieved from http://ascelibrary.org/doi/abs/10.1061/41130(369)281

13. Jiao, Y., Kishiki, S., Ene, D., Yamada, S., Kawamura, N., & Konishi, Y. (2014). *Plastic deformation capacity and hysteric behavior of U-shaped steel dampers for seismic isolated-buildings under dynamic cyclic loadings*. Retrieved from https://nees.org/resources/12190/download/10NCEE-001236.pdf

14. Kiran, A., Agrawal, M., & Reddy, G. (2016). Seismic Retrofitting of a Process Column Using Friction Dampers. *Procedia Engineering*, *144*, 1356-1363. http://dx.doi.org/10.1016/j.proeng.2016.05.165

15. Lago, A., Sullivan, T., & Calvi, G. (2012). *Deformed Shapes of Structures equipped with Viscous Dampers*. Retrieved from http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2541.pdf

16. Morgen, B., & Kurama, Y. (2008). Seismic Response Evaluation of Posttensioned Precast Concrete Frames with Friction Dampers. *Journal of Structural Engineering*, *134*(1), 132-145. http://dx.doi.org/10.1061/(asce)0733-9445(2008)134:1(132)

17. Naghshineh, A., Kassem, A., Pilorge, A., Galindo, O. R., & Bagchi, A. (2018). Seismic Performance of Reinforced Concrete Frame Buildings Equipped with Friction Dampers. Structures Congress 2018. doi:10.1061/9780784481325.011

18. *National building code of Canada, 2015*. (2015). Ottawa, Ont.

19. *NEHRP recommended provisions (National Earthquake Hazards Reduction Program) for seismic regulations for new buildings and other structures (FEMA 450)*. (2004). Washington, D.C.

20. Nie, J., Qin, K., & Xiao, V. (2006). Push-over analysis of the seismic behavior of a concrete-filled rectangular tubular frame structure. *Tsinghua Science and Technology*, *11*(1), 124-130. http://dx.doi.org/10.1016/s1007-0214(06)70165-1

21. Oyen, P., & Parker, J. (2009). *Seismic Rehabilitation of Extreme Soft-Story School Building with Friction Dampers Using the ASCE 41 Standard | Improving the Seismic Performance of Existing Buildings and Other Structures*. *Ascelibrary.org*. Retrieved from http://ascelibrary.org/doi/pdf/10.1061/41084(364)86

22. Pall, A., & Pall, R. (1996). *Friction-dampers for seismic control of buildings a Canadian experience*. *Iitk.ac.in*. Retrieved from http://www.iitk.ac.in/nicee/wcee/article/11_497.PDF

23. Pant, D. R., Wijeyewickrema, A. C. and ElGawady, M. A. (2013), Appropriate viscous damping for nonlinear time‐history analysis of base‐isolated reinforced concrete buildings. Earthquake Engng Struct. Dyn., 42: 2321-2339. doi:10.1002/eqe.2328

24. Patil, C., Patil, V., & Kharmale, S. (2015). *Performance-based plastic design of a high rise moment resisting frame with friction dampers*.

25. *PEER Ground Motion Database - PEER Center*. (2018). *Ngawest2.berkeley.edu*. Retrieved from https://ngawest2.berkeley.edu/

26. Plotner, S. (2017). *Building construction costs with RSMeans data 2017*.

27. Qiu, C., Li, H., Ji, K., Hou, H., & Tian, L. (2017). Performance-based plastic design approach for multi-story self-centering concentrically braced frames using SMA braces. *Engineering Structures*, *153*, 628-638. http://dx.doi.org/10.1016/j.engstruct.2017.10.068

28. Seismic Design with Friction Dampers - Quaketek | Earthquake protection Retrieved from: https://www.quaketek.com/seismic-design/

29. Seismic Energy Dissipation Devices. (2018). Retrieved from https://civil-engg-world.blogspot.ca/2011/03/seismic-energy-dissipation-devices.html

30. Shukla, K., & Dalal, S. (2017). Evaluation of Response Reduction Factor of a Reinforced Cement Concrete Building Designed by Performance Based Plastic Design Method and Limit State Design Method. *Procedia Engineering*, *173*, 1854-1861. http://dx.doi.org/10.1016/j.proeng.2016.12.235

31. Tatar, A., Niousha, A. & Rofooei, F.R. J Civil Struct Health Monit (2017) 7: 123. https://doi.org/10.1007/s13349-017-0209-8

32. The ATC-72-1 report, (2010). *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*, was developed under an agreement with the Pacific Earthquake Engineering Research Center (PEER).

33. Tirca, L. (2018). *Friction Dampers for Seismic Protections of Steel Buildings Subjected to Earthquakes: Emphasis on Structural Design*. Retrieved from https://doi.org/10.1007/978-3-642-36197-5_312-1

34. Whittle, J., Williams, M., & Blakeborough, A. (2012). Performance of Structural Members in Seismic Retrofitted Frames with Viscous Dampers. *15Th World Conference On Earthquake Engineering 2012 (15WCEE)*. Retrieved from http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2541.pdf

35. Wight, J. (2016). *Reinforced concrete*. Boston: Pearson.

Appendix A

Table A-0-1 Model (EL) internal beam reinforcement details

Story	Section	Location		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	700*600	End-INT	INT	4439	22	M15	2580	13	M15	10M@	200
		Middle		236	3	M15	1179	6	M15	10M@	125
13	850*700	End-INT		8654	43	M15	6257	31	M15	10M@	250
		Middle		921	5	M15	1742	9	M15	10M@	170
12	850*700	End-INT		11139	55	M15	8500	42	M15	10M@	235
		Middle		1338	7	M15	2015	10	M15	10M@	115
11	950*850	End-INT		15532	76	M15	12516	62	M15	10M@	280
		Middle		2211	11	M15	2679	14	M15	10M@	145
10	950*850	End-INT		18030	88	M15	14785	73	M15	10M@	255
		Middle		2211	8	M20	2874	10	M20	10M@	130
9	950*850	End-INT		20361	67	M20	17067	56	M20	10M@	280
		Middle		2211	8	M20	3135	11	M20	10M@	140
8	1000*800	End-INT		21263	70	M20	18836	62	M20	10M@	260
		Middle		2450	8	M20	3330	11	M20	10M@	135
7	1000*800	End-INT		21204	69	M20	18930	62	M20	10M@	295
		Middle		2465	9	M20	3327	11	M20	10M@	145
6	1100*950	End-INT		26269	86	M20	22622	74	M20	10M@	285

		Middle		3167	11	M20	4021	14	M20	10M@	150
5	1100*950	End-INT		26372	86	M20	22947	75	M20	10M@	300
		Middle		3334	11	M20	4183	14	M20	10M@	160
4	1100*950	End-INT		26621	87	M20	23667	77	M20	10M@	300
		Middle		3232	11	M20	4093	14	M20	10M@	160
3	1100*950	End-INT		26328	86	M20	23169	76	M20	10M@	300
		Middle		3118	11	M20	3974	13	M20	10M@	170
2	1100*950	End-INT		23221	76	M20	20565	67	M20	10M@	300
		Middle		2898	10	M20	3764	13	M20	10M@	200
1	1100*950	End-INT		14592	72	M15	12809	63	M15	10M@	410
		Middle		2361	12	M15	2688	14	M15	10M@	230

Table A-0-2 Model (EL) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	600*500	End-INT	EXT	3574	18	M15	2108	11	M15	10M@	170
		Middle		159	3	M15	797	4	M15	10M@	170
13	650*550	End-INT		6048	30	M15	4285	21	M15	10M@	185
		Middle		415	3	M15	1100	6	M15	10M@	185
12	700*600	End-INT		8311	41	M15	6444	32	M15	10M@	200

		Middle		585	3 M15	1255	7 M15	10M@ 200
11	700*600	End-INT		9053	45 M15	7067	35 M15	10M@ 200
		Middle		538	3 M15	1212	6 M15	10M@ 200
10	700*600	End-INT		10143	50 M15	7941	39 M15	10M@ 200
		Middle		795	4 M15	1401	7 M15	10M@ 200
9	750*650	End-INT		12490	61 M15	10762	53 M15	10M@ 220
		Middle		1008	5 M15	1555	8 M15	10M@ 220
8	800*650	End-INT		13976	69 M15	13005	64 M15	10M@ 235
		Middle		1043	6 M15	1566	8 M15	10M@ 185
7	800*650	End-INT		13780	68 M15	12659	62 M15	10M@ 235
		Middle		1128	6 M15	1613	8 M15	10M@ 215
6	850*700	End-INT		15077	74 M15	13347	66 M15	10M@ 250
		Middle		1195	6 M15	1660	9 M15	10M@ 180
5	850*700	End-INT		15024	74 M15	13313	65 M15	10M@ 250
		Middle		1117	6 M15	1597	8 M15	10M@ 205
4	850*700	End-INT		14894	73 M15	13065	64 M15	10M@ 250
		Middle		1210	6 M15	1651	9 M15	10M@ 165
3	850*700	End-INT		14171	70 M15	12382	61 M15	10M@ 250
		Middle		1194	6 M15	1620	8 M15	10M@ 185
2	850*700	End-INT		12428	61 M15	10845	53 M15	10M@ 250
		Middle		997	5 M15	1465	8 M15	10M@ 150
1	850*700	End-INT		7794	38 M15	6597	33 M15	10M@ 250

		Middle		687	4	M15	1219	6	M15	10M@	170

Table A-0-3 Model (EL-D) beam connected to dampers reinforcement details

Story	Section	Location		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B650*550	INT-END	DAMP	1981	12	M15	787	4	M15	10M@	185
		MIDDLE		196	3	M15	979	5	M15	10M@	185
13	B750*650	INT-END		3459	18	M15	1554	8	M15	10M@	440
		MIDDLE		329	3	M15	1335	7	M15	10M@	220
12	B800*700	INT-END		4824	24	M15	2921	15	M15	10M@	235
		MIDDLE		832	5	M15	1534	8	M15	10M@	470
11	B850*750	INT-END		6173	33	M15	4259	21	M15	10M@	250
		MIDDLE		1303	7	M15	1827	9	M15	10M@	250
10	B850*750	INT-END		7510	39	M15	5510	27	M15	10M@	500
		MIDDLE		1693	9	M15	2122	11	M15	10M@	395
9	B900*800	INT-END		8610	44	M15	6633	33	M15	10M@	265
		MIDDLE		1972	10	M15	2414	12	M15	10M@	480
8	B900*800	INT-END		9429	47	M15	7447	37	M15	10M@	265
		MIDDLE		1972	10	M15	2601	13	M15	10M@	265
7	B900*800	INT-END		10352	50	M15	8287	40	M15	10M@	480

		MIDDLE		1972	7	M20	2792	10	M20	10M@	265
6	B900*800	INT-END		11152	54	M15	9072	44	M15	10M@	265
		MIDDLE		2152	8	M20	2980	10	M20	10M@	265
5	B950*850	INT-END		12450	64	M15	10402	50	M15	10M@	280
		MIDDLE		2499	9	M20	3313	11	M20	10M@	245
4	B950*850	INT-END		13069	64	M15	11035	54	M15	10M@	460
		MIDDLE		2661	14	M15	3464	17	M15	10M@	275
3	B1000*800	INT-END		13580	69	M15	11602	56	M15	10M@	295
		MIDDLE		2790	14	M15	3552	18	M15	10M@	460
2	B1000*800	INT-END		12470	64	M15	10650	52	M15	10M@	295
		MIDDLE		2616	13	M15	3364	17	M15	10M@	235
1	B1000*800	INT-END		9180	44	M15	7570	38	M15	10M@	295
		MIDDLE		2191	11	M15	2702	14	M15	10M@	265

Table A-0-4 Model (EL-D) internal beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B650*550	INT-END	INT	5635	30	M15	3151	16	M15	10M@	185
		MIDDLE		738	4	M15	1497	8	M15	10M@	130
13	B750*650	INT-END		9723	49	M15	6906	34	M15	10M@	195
		MIDDLE		1413	7	M15	2347	12	M15	10M@	220

12	B800*700	INT-END		13013	64	M15	9958	48	M15	10M@	235
		MIDDLE		2076	11	M15	2990	15	M15	10M@	145
11	B850*750	INT-END		16119	78	M15	13146	64	M15	10M@	250
		MIDDLE		2715	14	M15	3617	18	M15	10M@	170
10	B850*750	INT-END		17082	83	M15	15034	73	M15	10M@	210
		MIDDLE		3023	15	M15	3930	20	M15	10M@	235
9	B900*800	INT-END		19441	88	M15	17755	84	M15	10M@	265
		MIDDLE		3568	18	M15	4459	22	M15	10M@	160
8	B900*800	INT-END		19731	88	M15	18512	84	M15	10M@	405
		MIDDLE		3726	21	M15	4609	23	M15	10M@	175
7	B900*800	INT-END		20024	69	M20	19237	62	M20	10M@	210
		MIDDLE		3806	21	M15	4692	23	M15	10M@	230
6	B900*800	INT-END		19963	69	M20	19213	62	M20	10M@	265
		MIDDLE		3865	21	M15	4739	24	M15	10M@	180
5	B950*850	INT-END		21894	74	M20	20802	67	M20	10M@	440
		MIDDLE		4282	21	M15	5137	26	M15	10M@	205
4	B950*850	INT-END		21296	93	M15	19562	89	M15	10M@	225
		MIDDLE		4191	21	M15	5030	25	M15	10M@	250
3	B1000*800	INT-END		20738	98	M15	18714	90	M15	10M@	295
		MIDDLE		4067	21	M15	4858	24	M15	10M@	235
2	B1000*800	INT-END		17362	88	M15	15070	73	M15	10M@	460
		MIDDLE		3511	18	M15	4276	21	M15	10M@	265

1	B1000*800	INT-END		11486	56	M15	9716	47	M15	10M@	270
		MIDDLE		2461	13	M15	3227	16	M15	10M@	305

Table A-0-5 Model (EL-D) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B550*450	INT-END		2413	14	M15	971	5	M15	10M@	155
		MIDDLE		268	2	M15	678	4	M15	10M@	155
13	B650*550	INT-END		4192	21	M15	2635	13	M15	10M@	185
		MIDDLE		196	3	M15	979	5	M15	10M@	140
12	B650*550	INT-END		4877	24	M15	3262	16	M15	10M@	185
		MIDDLE		196	3	M15	979	5	M15	10M@	160
11	B650*550	INT-END		5362	27	M15	3684	19	M15	10M@	185
		MIDDLE		330	3	M15	1046	6	M15	10M@	185
10	B650*550	INT-END		5972	30	M15	4225	21	M15	10M@	185
		MIDDLE		450	3	M15	1114	6	M15	10M@	140
9	B650*550	INT-END		6397	33	M15	4585	23	M15	10M@	185
		MIDDLE		478	3	M15	1142	6	M15	10M@	155
8	B750*650	INT-END		8429	44	M15	6703	33	M15	10M@	220
		MIDDLE		697	4	M15	1335	7	M15	10M@	220
7	B750*650	INT-END		9315	49	M15	7475	37	M15	10M@	220

		MIDDLE		828	5	M15	1406	7	M15	10M@	155
6	B800*700	INT-END		10309	54	M15	8544	41	M15	10M@	235
		MIDDLE		1033	6	M15	1558	8	M15	10M@	185
5	B800*700	INT-END		10116	49	M15	8375	41	M15	10M@	235
		MIDDLE		919	5	M15	1534	8	M15	10M@	235
4	B800*700	INT-END		9780	49	M15	8102	39	M15	10M@	235
		MIDDLE		967	5	M15	1534	8	M15	10M@	165
3	B800*700	INT-END		9303	49	M15	7674	38	M15	10M@	235
		MIDDLE		969	5	M15	1534	8	M15	10M@	180
2	B800*700	INT-END		8273	41	M15	6812	34	M15	10M@	235
		MIDDLE		745	4	M15	1534	8	M15	10M@	235
1	B800*700	INT-END		6027	30	M15	4756	24	M15	10M@	235
		MIDDLE		506	3	M15	1494	8	M15	10M@	145

Table A-0-6 Model (MD) internal beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B550X400	INT-END	INT	1848	10	M15	781	4	M15	10M@	155
		MIDDLE		346	2	M15	827	5	M15	10M@	155
13	B650X450	INT-END		2558	13	M15	937	5	M15	10M@	185
		MIDDLE		178	3	M15	892	5	M15	10M@	185

12	B700X500	INT-END		2971	15	M15	1206	7	M15	10M@	200
		MIDDLE		196	3	M15	982	5	M15	10M@	200
11	B700X500	INT-END		3267	11	M20	1409	5	M20	10M@	200
		MIDDLE		208	3	M20	1042	4	M20	10M@	200
10	B750X600	INT-END		4045	14	M20	2121	7	M20	10M@	220
		MIDDLE		393	3	M20	1232	5	M20	10M@	220
9	B750X600	INT-END		4208	14	M20	2304	8	M20	10M@	220
		MIDDLE		454	3	M20	1271	5	M20	10M@	220
8	B800X650	INT-END		4700	17	M20	2813	12	M20	10M@	235
		MIDDLE		628	3	M20	1424	5	M20	10M@	235
7	B800X650	INT-END		4834	16	M20	3007	11	M20	10M@	235
		MIDDLE		698	3	M20	1435	5	M20	10M@	235
6	B800X650	INT-END		5094	11	M25	3233	7	M25	10M@	235
		MIDDLE		769	3	M25	1493	4	M25	10M@	235
5	B800X650	INT-END		5253	11	M25	3371	7	M25	10M@	235
		MIDDLE		810	3	M25	1525	4	M25	10M@	235
4	B800X650	INT-END		5091	11	M25	3313	7	M25	10M@	235
		MIDDLE		804	3	M25	1518	4	M25	10M@	235
3	B850X700	INT-END		5432	11	M25	3684	8	M25	10M@	250
		MIDDLE		938	3	M25	1629	4	M25	10M@	250
2	B850X700	INT-END		4710	16	M20	3083	11	M20	10M@	250
		MIDDLE		734	3	M20	1629	6	M20	10M@	250

1	B850X700	INT-END		2929	16	M15	1629	8	M15	10M@	250
		MIDDLE		293	3	M15	1466	8	M15	10M@	250

Table A-0-7 Model (MD) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B500X350	INT-END	EXT	1289	7	M15	529	3	M15	10M@	140
		MIDDLE		157	2	M15	536	3	M15	10M@	140
13	B550X400	INT-END		1797	10	M15	676	4	M15	10M@	155
		MIDDLE		121	2	M15	606	3	M15	10M@	155
12	B650X450	INT-END		2333	12	M15	1173	6	M15	10M@	185
		MIDDLE		195	3	M15	801	4	M15	10M@	185
11	B650X450	INT-END		2545	13	M15	1362	7	M15	10M@	185
		MIDDLE		252	3	M15	801	4	M15	10M@	185
10	B650X450	INT-END		2655	9	M20	1470	5	M20	10M@	185
		MIDDLE		289	3	M20	806	3	M20	10M@	185
9	B650X450	INT-END		2715	14	M15	1550	9	M15	10M@	185
		MIDDLE		315	3	M15	825	5	M15	10M@	185
8	B700X500	INT-END		3164	11	M20	1997	7	M20	10M@	200
		MIDDLE		465	3	M20	959	4	M20	10M@	200
7	B700X500	INT-END		3236	11	M20	2109	7	M20	10M@	200

		MIDDLE		504	3	M20	967	4	M20	10M@	200
6	B700X500	INT-END		3371	12	M20	2232	8	M20	10M@	200
		MIDDLE		541	3	M20	996	4	M20	10M@	200
5	B700X500	INT-END		3487	12	M20	2339	8	M20	10M@	200
		MIDDLE		575	3	M20	1021	4	M20	10M@	200
4	B700X500	INT-END		3341	12	M20	2253	8	M20	10M@	200
		MIDDLE		554	3	M20	1005	4	M20	10M@	200
3	B700X500	INT-END		3114	11	M20	2051	7	M20	10M@	200
		MIDDLE		491	3	M20	959	4	M20	10M@	200
2	B700X500	INT-END		2711	14	M15	1685	9	M15	10M@	200
		MIDDLE		374	3	M15	959	5	M15	10M@	200
1	B700X500	INT-END		1787	10	M15	959	6	M15	10M@	200
		MIDDLE		178	3	M15	891	5	M15	10M@	200

Table A-0-8 Model (MD-D) beam connected to dampers reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B500*400	INT-END	DAMP	1729	6	M20	576	2	M20	10M@	140
		MIDDLE		482	2	M20	924	4	M20	10M@	140
13	B550*400	INT-END		1956	7	M20	652	3	M20	10M@	155
		MIDDLE		361	2	M20	993	4	M20	10M@	155

12	B650*500	INT-END		2152	12 M15	868	5 M15	10M@ 185
		MIDDLE		185	3 M15	927	4 M15	10M@ 185
11	B650*500	INT-END		2452	9 M20	890	3 M20	10M@ 185
		MIDDLE		186	3 M20	932	4 M20	10M@ 185
10	B650*500	INT-END		2658	9 M20	890	3 M20	10M@ 185
		MIDDLE		186	3 M20	930	4 M20	10M@ 185
9	B700*600	INT-END		2836	11 M20	1150	5 M20	10M@ 200
		MIDDLE		230	3 M20	1150	5 M20	10M@ 200
8	B700*600	INT-END		2997	11 M20	1150	4 M20	10M@ 200
		MIDDLE		230	3 M20	1150	5 M20	10M@ 200
7	B700*600	INT-END		3302	7 M25	1337	3 M25	10M@ 200
		MIDDLE		230	3 M25	1150	5 M25	10M@ 200
6	B700*600	INT-END		3558	8 M25	1561	3 M25	10M@ 200
		MIDDLE		290	3 M25	1150	5 M25	10M@ 200
5	B700*600	INT-END		3759	8 M25	1737	4 M25	10M@ 200
		MIDDLE		349	3 M25	1167	5 M25	10M@ 200
4	B700*600	INT-END		3868	8 M25	1860	4 M25	10M@ 200
		MIDDLE		392	3 M25	1195	5 M25	10M@ 200
3	B700*600	INT-END		3913	8 M25	1899	4 M25	10M@ 200
		MIDDLE		404	3 M25	1204	5 M25	10M@ 200
2	B700*600	INT-END		3714	8 M25	1724	4 M25	10M@ 200
		MIDDLE		347	3 M25	1157	5 M25	10M@ 200

1	B700*600	INT-END		2694	10	M20	1150	4	M20	10M@	200
		MIDDLE		230	3	M20	1150	5	M20	10M@	200

Table A-0-9 Model (MD-D) internal beam reinforcement details

Story	Section	Location		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B500*400	INT-END	INT	2127	8	M20	709	3	M20	10M@	140
		MIDDLE		238	2	M20	1083	4	M20	10M@	140
13	B550*400	INT-END		2712	10	M20	904	3	M20	10M@	155
		MIDDLE		216	2	M20	1081	4	M20	10M@	155
12	B650*500	INT-END		3300	12	M20	1163	4	M20	10M@	185
		MIDDLE		404	3	M20	1100	4	M20	10M@	185
11	B650*500	INT-END		3696	8	M25	1461	3	M25	10M@	185
		MIDDLE		546	3	M25	1165	4	M25	10M@	185
10	B650*500	INT-END		3929	8	M25	1650	4	M25	10M@	185
		MIDDLE		637	3	M25	1265	4	M25	10M@	185
9	B700*600	INT-END		4320	9	M25	2159	5	M25	10M@	200
		MIDDLE		901	3	M25	1431	5	M25	10M@	200
8	B700*600	INT-END		4460	9	M25	2280	5	M25	10M@	200
		MIDDLE		1006	3	M25	1486	5	M25	10M@	200
7	B700*600	INT-END		4731	10	M25	2574	5	M25	10M@	200

		MIDDLE		1133	3	M25	1564	5	M25	10M@	200
6	B700*600	INT-END		4962	11	M25	2772	6	M25	10M@	200
		MIDDLE		1150	3	M25	1618	5	M25	10M@	200
5	B700*600	INT-END		5066	10	M25	2860	6	M25	10M@	200
		MIDDLE		1150	3	M25	1694	4	M25	10M@	200
4	B700*600	INT-END		5041	10	M25	2870	6	M25	10M@	200
		MIDDLE		1150	3	M25	1715	4	M25	10M@	200
3	B700*600	INT-END		4924	10	M25	2770	6	M25	10M@	200
		MIDDLE		1150	3	M25	1707	5	M25	10M@	200
2	B700*600	INT-END		4505	9	M25	2408	5	M25	10M@	200
		MIDDLE		1150	3	M25	1617	5	M25	10M@	200
1	B700*600	INT-END		3099	12	M20	1214	5	M20	10M@	200
		MIDDLE		704	3	M20	1167	5	M20	10M@	200

Table A-0-10 Model (MD-D) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B450*400	INT-END	EXT	1475	8	M15	493	3	M15	10M@	125
		MIDDLE		176	2	M15	735	4	M15	10M@	125
13	B450*400	INT-END		1876	8	M20	625	3	M20	10M@	125
		MIDDLE		144	2	M20	720	4	M20	10M@	125

12	B500*400	INT-END		1969	7 M20	656	3 M20	10M@ 140
		MIDDLE		173	2 M20	682	4 M20	10M@ 140
11	B500*400	INT-END		2111	8 M20	704	3 M20	10M@ 140
		MIDDLE		255	2 M20	701	4 M20	10M@ 140
10	B500*400	INT-END		2284	8 M20	761	3 M20	10M@ 140
		MIDDLE		312	2 M20	761	4 M20	10M@ 140
9	B600*500	INT-END		2747	10 M20	1286	5 M20	10M@ 170
		MIDDLE		584	2 M20	980	4 M20	10M@ 170
8	B600*500	INT-END		2923	6 M25	1431	3 M25	10M@ 170
		MIDDLE		693	2 M25	1037	4 M25	10M@ 170
7	B600*500	INT-END		3068	7 M25	1577	3 M25	10M@ 170
		MIDDLE		704	2 M25	1063	4 M25	10M@ 170
6	B600*500	INT-END		3188	7 M25	1681	4 M25	10M@ 170
		MIDDLE		803	2 M25	1107	4 M25	10M@ 170
5	B600*500	INT-END		3306	7 M25	1783	4 M25	10M@ 170
		MIDDLE		822	2 M25	1183	4 M25	10M@ 170
4	B650*500	INT-END		3547	7 M25	2107	5 M25	10M@ 185
		MIDDLE		890	3 M25	1266	4 M25	10M@ 185
3	B650*500	INT-END		3554	7 M25	2113	5 M25	10M@ 185
		MIDDLE		890	3 M25	1281	4 M25	10M@ 185
2	B650*500	INT-END		3257	7 M25	1878	4 M25	10M@ 185
		MIDDLE		890	3 M25	1223	4 M25	10M@ 185

1	B650*500	INT-END		2271	8	M20	1020	4	M20	10M@	185
		MIDDLE		551	3	M20	894	4	M20	10M@	185

Table A-0-11 Model (DUC) internal beam reinforcement details

Story	Section	Location		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B500*450	INT-END	INT	1795.0	10	M15	995	6	M15	10M@	105
		MIDDLE		400.0	2	M15	995	6	M15	10M@	225
13	B600*500	INT-END		1922.7	10	M15	983	6	M15	10M@	125
		MIDDLE		400.0	2	M15	983	6	M15	10M@	275
12	B600*500	INT-END		2081.0	12	M15	969	6	M15	10M@	125
		MIDDLE		400.0	2	M15	969	6	M15	10M@	255
11	B650*550	INT-END		2314.9	12	M15	1156	6	M15	10M@	125
		MIDDLE		400.0	2	M15	1156	6	M15	10M@	250
10	B650*550	INT-END		2450.2	14	M15	1156	6	M15	10M@	125
		MIDDLE		400.0	2	M15	1156	6	M15	10M@	230
9	B700*600	INT-END		2632.7	14	M15	1366	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1366	8	M15	10M@	205
8	B700*600	INT-END		2766.8	14	M15	1366	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1366	8	M15	10M@	205
7	B700*600	INT-END		2868.1	16	M15	1366	8	M15	10M@	125

		MIDDLE		400.0	2	M15	1366	8	M15	10M@	190
6	B700*600	INT-END		2918.0	16	M15	1366	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1366	8	M15	10M@	185
5	B750*600	INT-END		3021.8	16	M15	1471	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1471	8	M15	10M@	185
4	B750*600	INT-END		3038.1	16	M15	1471	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1471	8	M15	10M@	185
3	B750*600	INT-END		3030.3	16	M15	1471	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1471	8	M15	10M@	185
2	B750*600	INT-END		2939.9	16	M15	1471	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1471	8	M15	10M@	185
1	B750*600	INT-END		2686.8	14	M15	1471	8	M15	10M@	125
		MIDDLE		400.0	2	M15	1471	8	M15	10M@	195

Table A-0-12 Model (DUC) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B500*450	INT-END	EXT	1211	8	M15	710	4	M15	10M@	105
		MIDDLE		400	2	M15	710	4	M15	10M@	225
13	B600*500	INT-END		1540	8	M15	964	6	M15	10M@	125
		MIDDLE		400	2	M15	964	6	M15	10M@	275

12	B600*500	INT-END		2050	12	M15	964	6	M15	10M@	125
		MIDDLE		400	2	M15	964	6	M15	10M@	270
11	B650*550	INT-END		1982	12	M15	1156	6	M15	10M@	125
		MIDDLE		400	2	M15	1156	6	M15	10M@	265
10	B650*550	INT-END		2102	12	M15	1156	6	M15	10M@	125
		MIDDLE		400	2	M15	1156	6	M15	10M@	265
9	B700*600	INT-END		2304	12	M15	1366	8	M15	10M@	125
		MIDDLE		400	2	M15	1366	8	M15	10M@	235
8	B700*600	INT-END		2418	14	M15	1366	8	M15	10M@	125
		MIDDLE		400	2	M15	1366	8	M15	10M@	215
7	B700*600	INT-END		2551	14	M15	1366	8	M15	10M@	125
		MIDDLE		400	2	M20	1366	8	M20	10M@	215
6	B700*600	INT-END		2631	14	M15	1366	8	M15	10M@	125
		MIDDLE		400	2	M20	1366	8	M20	10M@	215
5	B750*600	INT-END		2739	14	M15	1471	8	M15	10M@	125
		MIDDLE		400	2	M20	1471	8	M20	10M@	215
4	B750*600	INT-END		2744	14	M15	1471	8	M15	10M@	125
		MIDDLE		400	2	M15	1471	8	M15	10M@	215
3	B750*600	INT-END		2757	14	M15	1471	8	M15	10M@	125
		MIDDLE		400	2	M15	1471	8	M15	10M@	210
2	B750*600	INT-END		2700	14	M15	1471	8	M15	10M@	125
		MIDDLE		400	2	M15	1471	8	M15	10M@	210

1	B750*600	INT-END		2328	12	M15	1471	8	M15	10M@	125
		MIDDLE		400	2	M15	1471	8	M15	10M@	230

Table A-0-13 Model (DUC-D) internal beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B450*450	INT-END	INT	2119	8	M20	1082	4	M20	10M@	150
		MIDDLE		400	2	M20	1082	4	M20	10M@	299
13	B450*450	INT-END		1967	7	M20	1043	4	M20	10M@	150
		MIDDLE		400	2	M20	1043	4	M20	10M@	236
12	B450*450	INT-END		2098	7	M20	1032	4	M20	10M@	150
		MIDDLE		400	2	M20	1032	4	M20	10M@	299
11	B600*500	INT-END		2262	8	M20	1035	4	M20	10M@	150
		MIDDLE		400	2	M20	1035	4	M20	10M@	235
10	B600*500	INT-END		2279	8	M20	1042	4	M20	10M@	160
		MIDDLE		400	2	M20	1042	4	M20	10M@	308
9	B650*550	INT-END		2385	8	M20	1152	4	M20	10M@	160
		MIDDLE		400	2	M20	1152	4	M20	10M@	218
8	B650*550	INT-END		2471	9	M20	1152	4	M20	10M@	160
		MIDDLE		400	2	M20	1152	4	M20	10M@	308
7	B650*550	INT-END		2526	9	M20	1165	4	M20	10M@	160

		MIDDLE		400	2	M20	1165	4	M20	10M@	218
6	B650*550	INT-END		2496	9	M20	1152	4	M20	10M@	160
		MIDDLE		400	2	M20	1152	4	M20	10M@	306
5	B700*600	INT-END		2606	9	M20	1362	5	M20	10M@	160
		MIDDLE		400	2	M20	1362	5	M20	10M@	216
4	B700*600	INT-END		2560	9	M20	1362	5	M20	10M@	160
		MIDDLE		400	2	M20	1362	5	M20	10M@	285
3	B700*600	INT-END		2512	9	M20	1362	5	M20	10M@	160
		MIDDLE		400	2	M20	1362	5	M20	10M@	216
2	B700*600	INT-END		2421	9	M20	1362	5	M20	10M@	160
		MIDDLE		400	2	M20	1362	5	M20	10M@	301
1	B700*600	INT-END		2333	8	M20	1362	5	M20	10M@	160
		MIDDLE		400	2	M20	1362	5	M20	10M@	224

Table A-0-14 Model (DUC-D) external beam reinforcement details

Story	**Section**	**Location**		TOP REINFORCEMENT			BOTTOM REINFORCEMENT			stirrups	
				AsT	**#bars**	**Bars size**	**AsB**	**#bars**	**Bars size**	**Bars size**	**spacing**
14	B450*450	INT-END	EXT	1273	5	M20	736	3	M20	10M@	100
		MIDDLE		400	2	M20	736	3	M20	10M@	199
13	B450*450	INT-END		1107	4	M20	785	3	M20	10M@	93
		MIDDLE		400	2	M20	785	3	M20	10M@	199

12	B450*450	INT-END		1168	4 M20	785	3 M20	10M@ 125
		MIDDLE		400	2 M20	785	3 M20	10M@ 249
11	B600*500	INT-END		1255	5 M20	960	4 M20	10M@ 125
		MIDDLE		400	2 M20	960	4 M20	10M@ 249
10	B600*500	INT-END		1263	5 M20	960	4 M20	10M@ 125
		MIDDLE		400	2 M20	960	4 M20	10M@ 249
9	B650*550	INT-END		1287	5 M20	1152	4 M20	10M@ 125
		MIDDLE		400	2 M20	1152	4 M20	10M@ 249
8	B650*550	INT-END		1360	5 M20	1152	4 M20	10M@ 137
		MIDDLE		400	2 M20	1152	4 M20	10M@ 274
7	B650*550	INT-END		1419	5 M20	1152	4 M20	10M@ 137
		MIDDLE		400	2 M20	1152	4 M20	10M@ 259
6	B650*550	INT-END		1445	5 M20	1152	4 M20	10M@ 137
		MIDDLE		400	2 M20	1152	4 M20	10M@ 274
5	B700*600	INT-END		1496	5 M20	1362	5 M20	10M@ 137
		MIDDLE		400	2 M20	1362	5 M20	10M@ 259
4	B700*600	INT-END		1479	5 M20	1362	5 M20	10M@ 150
		MIDDLE		400	2 M20	1362	5 M20	10M@ 299
3	B700*600	INT-END		1496	5 M20	1362	5 M20	10M@ 150
		MIDDLE		400	2 M20	1362	5 M20	10M@ 255
2	B700*600	INT-END		1507	6 M20	1362	5 M20	10M@ 150
		MIDDLE		400	2 M20	1362	5 M20	10M@ 299

1	B700*600	INT-END		1460	5	M20	1362	5	M20	10M@	150
		MIDDLE		400	2	M20	1362	5	M20	10M@	236

Columns hand calculations

The hand-calculation done for the reinforcement of columns was used using the excel data sheet of my co-worker Amina Kassem. I found my own results, using her excel sheet for the calculations steps. Final answers of reinforcement for columns are in the table 7-1 to 7-14.

Table A-0-15 Model (EL) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	600	corner	4	20	M20	**M10@**	170.00
13	600	corner	4	32	M20	**M10@**	120.00
12	600	corner	4	24	M20	**M10@**	135.00
11	600	corner	4	24	M20	**M10@**	125.00
10	650	corner	4	16	M30	**M10@**	90.00
9	650	corner	4	20	M30	**M10@**	85.00
8	650	corner	4	20	M30	**M10@**	75.00
7	700	corner	4	20	M30	**M10@**	80.00
6	700	corner	4	20	M30	**M10@**	75.00
5	700	corner	4	20	M30	**M10@**	75.00
4	750	corner	4	20	M30	**M10@**	75.00
3	750	corner	6	36	M30	**M10@**	80.00
2	750	corner	4	28	M30	**M10@**	85.00
1	1000	corner	5	32	M30	**M10@**	110.00

Table A-0-16 Model (EL) external columns reinforcement

			FLEXURAL REINFORCMENT	SHEAR REINFORCMENT

Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	700	external	4	20	M25	**M10@**	90.00
13	700	external	4	32	M25	**M10@**	70.00
12	850	external	5	32	M25	**M10@**	65.00
11	850	external	4	28	M30	**M10@**	50.00
10	850	external	4	28	M30	**M10@**	50.00
9	1000	external	5	28	M30	**M10@**	50.00
8	1000	external	5	32	M30	**M10@**	40.00
7	1100	external	6	32	M30	**M10@**	45.00
6	1100	external	6	20	M30	**M10@**	45.00
5	1200	external	7	24	M30	**M10@**	40.00
4	1200	external	7	24	M30	**M10@**	50.00
3	1350	external	8	24	M30	**M10@**	40.00
2	1350	external	6	40	M40	**M10@**	40.00
1	1500	external	5	40	M45	**M10@**	55.00

Table A-0-17 Model (EL) internal columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	800	internal	5	28	M25	**M10@**	65.00
13	800	internal	4	20	M40	**M10@**	45.00
12	950	internal	4	28	M40	**M10@**	40.00
11	950	internal	4	28	M40	**M10@**	30.00
10	1000	internal	4	32	M40	**M10@**	25.00
9	1100	internal	5	32	M40	**M10@**	25.00

8	1100	internal	5	36	M40	**M10@**	25.00
7	1200	internal	5	40	M40	**M10@**	25.00
6	1200	internal	5	40	M40	**M10@**	20.00
5	1350	internal	5	36	M40	**M10@**	20.00
4	1350	internal	6	36	M40	**M10@**	20.00
3	1350	internal	6	36	M40	**M10@**	25.00
2	1350	internal	5	32	M45	**M10@**	25.00
1	1700	internal	4	36	M55	**M10@**	30.00

Table A-0-18 Model (EL-D) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	500	corner	4	16	M20	M10@	140.00
13	500	corner	4	24	M20	M10@	140.00
12	500	corner	4	12	M20	M10@	140.00
11	600	corner	4	16	M20	M10@	135.00
10	600	corner	4	12	M20	M10@	170.00
9	600	corner	4	28	M20	M10@	110.00
8	600	corner	5	28	M20	M10@	115.00
7	650	corner	5	36	M20	M10@	85.00
6	650	corner	5	36	M20	M10@	90.00
5	650	corner	5	36	M20	M10@	90.00
4	700	corner	6	36	M20	M10@	95.00

3	700	corner	6	36	M20	M10@	95.00
2	700	corner	6	36	M20	M10@	120.00
1	950	corner	6	36	M25	M10@	120.00

Table A-0-19 Model (EL-D) external columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	600	external	5	28	M20	M10@	110.00
13	600	external	4	36	M20	M10@	85.00
12	650	external	4	36	M25	M10@	70.00
11	650	external	4	36	M25	M10@	60.00
10	700	external	4	36	M25	M10@	50.00
9	700	external	4	36	M25	M10@	50.00
8	800	external	5	36	M25	M10@	50.00
7	800	external	4	36	M30	M10@	50.00
6	850	external	4	36	M30	M10@	50.00
5	850	external	4	36	M30	M10@	45.00
4	900	external	4	36	M30	M10@	50.00
3	900	external	4	44	M30	M10@	50.00
2	1050	external	5	36	M30	M10@	55.00
1	1250	external	7	48	M30	M10@	65.00

Table A-0-20 Model (EL-D) internal columns reinforcement

			FLEXURAL REINFORCMENT	SHEAR REINFORCMENT

Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	700	internal	4	16	M25	M10@	120.00
13	700	internal	4	28	M25	M10@	75.00
12	800	internal	4	28	M30	M10@	60.00
11	800	internal	4	28	M30	M10@	50.00
10	850	internal	4	36	M30	M10@	40.00
9	850	internal	4	40	M30	M10@	35.00
8	950	internal	4	20	M55	M10@	40.00
7	950	internal	4	24	M55	M10@	35.00
6	1050	internal	4	24	M55	M10@	40.00
5	1050	internal	4	24	M55	M10@	35.00
4	1150	internal	5	24	M55	M10@	35.00
3	1150	internal	4	24	M45	M10@	35.00
2	1250	internal	4	24	M45	M10@	40.00
1	1400	internal	5	48	M45	M10@	50.00

Table A-0-21 Model (EL-D) internal connected to dampers columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	700	connected to dampers	4	24	M25	M10@	95.00
13	700	connected to dampers	4	36	M25	M10@	65.00
12	800	connected to dampers	4	36	M30	M10@	50.00
11	800	connected to dampers	4	36	M30	M10@	40.00
10	850	connected to dampers	4	40	M30	M10@	35.00

9	850	connected to dampers	4	40	M30	M10@	35.00
8	950	connected to dampers	4	36	M55	M10@	35.00
7	950	connected to dampers	4	36	M55	M10@	35.00
6	1050	connected to dampers	4	40	M55	M10@	35.00
5	1050	connected to dampers	4	40	M55	M10@	30.00
4	1150	connected to dampers	4	36	M45	M10@	35.00
3	1150	connected to dampers	4	48	M45	M10@	30.00
2	1250	connected to dampers	4	48	M45	M10@	35.00
1	1400	connected to dampers	4	36	M55	M10@	45.00

Table A-0-22 Model (MD) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	500	corner	5	16	M15	M10@	140.00
13	500	corner	5	16	M15	M10@	140.00
12	550	corner	5	16	M15	M10@	150.00
11	550	corner	5	16	M15	M10@	150.00
10	550	corner	5	16	M15	M10@	150.00
9	600	corner	6	20	M15	M10@	170.00
8	600	corner	6	20	M15	M10@	170.00
7	650	corner	7	24	M15	M10@	180.00
6	650	corner	7	24	M15	M10@	180.00
5	650	corner	7	24	M15	M10@	180.00
4	700	corner	6	20	M20	M10@	200.00
3	700	corner	6	20	M20	M10@	200.00
2	700	corner	6	20	M20	M10@	200.00

1	850	corner	8	36	M20	M10@	240.00

Table A-0-23 Model (MD) external columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	600	external	6	20	M15	M10@	170.00
13	600	external	6	20	M15	M10@	170.00
12	700	external	6	20	M20	M10@	180.00
11	700	external	6	20	M20	M10@	180.00
10	700	external	6	20	M20	M10@	170.00
9	750	external	6	20	M20	M10@	165.00
8	750	external	6	20	M20	M10@	150.00
7	850	external	5	16	M25	M10@	170.00
6	850	external	5	16	M25	M10@	165.00
5	850	external	5	16	M25	M10@	155.00
4	950	external	6	20	M25	M10@	195.00
3	950	external	6	20	M25	M10@	200.00
2	950	external	6	20	M25	M10@	175.00
1	1200	external	7	24	M30	M10@	175.00

Table A-0-24 Model (MD) internal columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	650	internal	7	24	M15	M10@	180.00

13	650	internal	7	24	M15	M10@	180.00
12	750	internal	6	20	M20	M10@	210.00
11	750	internal	6	20	M20	M10@	180.00
10	750	internal	4	12	M25	M10@	145.00
9	800	internal	5	16	M25	M10@	140.00
8	800	internal	5	16	M25	M10@	130.00
7	900	internal	6	20	M25	M10@	135.00
6	900	internal	6	20	M25	M10@	130.00
5	900	internal	6	20	M25	M10@	125.00
4	1000	internal	6	20	M25	M10@	135.00
3	1000	internal	6	20	M25	M10@	130.00
2	1000	internal	6	20	M25	M10@	135.00
1	1300	internal	4	12	M45	M10@	165.00

Table A-0-25 Model (MD-D) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	400	corner	4	16	M15	M10@	100.00
13	400	corner	4	12	M15	M10@	100.00
12	450	corner	4	12	M15	M10@	120.00
11	450	corner	4	12	M15	M10@	120.00
10	450	corner	4	12	M15	M10@	120.00
9	500	corner	5	16	M15	M10@	140.00
8	500	corner	5	16	M15	M10@	140.00
7	500	corner	5	16	M15	M10@	140.00
6	550	corner	5	16	M15	M10@	150.00

5	550	corner	5	16	M15	M10@	150.00
4	550	corner	5	16	M15	M10@	150.00
3	600	corner	6	20	M15	M10@	170.00
2	600	corner	4	16	M20	M10@	170.00
1	750	corner	6	20	M20	M10@	210.00

Table A-0-26 Model (MD-D) external columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	500	external	5	24	M15	M10@	140.00
13	500	external	5	20	M15	M10@	140.00
12	550	external	5	20	M15	M10@	150.00
11	550	external	5	20	M15	M10@	150.00
10	550	external	6	28	M15	M10@	140.00
9	600	external	6	24	M15	M10@	125.00
8	600	external	7	28	M15	M10@	120.00
7	650	external	8	28	M15	M10@	125.00
6	650	external	8	28	M15	M10@	120.00
5	650	external	8	28	M15	M10@	120.00
4	700	external	9	28	M15	M10@	125.00
3	700	external	8	32	M15	M10@	125.00
2	700	external	6	32	M20	M10@	125.00
1	1000	external	6	20	M25	M10@	210.00

Table A-0-27 Model (MD-D) internal columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)

	B=H (mm)						
14	550	internal	5	16	M15	M10@	150.00
13	550	internal	5	16	M15	M10@	150.00
12	650	internal	7	24	M15	M10@	180.00
11	650	internal	7	24	M15	M10@	180.00
10	650	internal	7	24	M15	M10@	180.00
9	700	internal	9	28	M15	M10@	200.00
8	700	internal	9	28	M15	M10@	180.00
7	800	internal	9	32	M15	M10@	195.00
6	800	internal	9	32	M15	M10@	180.00
5	800	internal	9	32	M15	M10@	165.00
4	850	internal	9	28	M20	M10@	175.00
3	850	internal	9	28	M20	M10@	165.00
2	850	internal	5	24	M25	M10@	160.00
1	1100	internal	6	20	M30	M10@	190.00

Table A-0-28 Model (MD-D) internal connected to dampers columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	550	connected to dampers	5	16	M15	M10@	150.00
13	550	connected to dampers	5	16	M15	M10@	150.00
12	650	connected to dampers	7	24	M15	M10@	180.00
11	650	connected to dampers	7	24	M15	M10@	180.00
10	650	connected to dampers	7	24	M15	M10@	175.00
9	700	connected to dampers	9	28	M15	M10@	180.00
8	700	connected to dampers	9	28	M15	M10@	165.00

7	800	connected to dampers	9	32	M15	M10@	180.00
6	800	connected to dampers	9	32	M15	M10@	165.00
5	800	connected to dampers	9	32	M15	M10@	155.00
4	850	connected to dampers	9	28	M20	M10@	165.00
3	850	connected to dampers	8	32	M20	M10@	160.00
2	850	connected to dampers	5	32	M25	M10@	155.00
1	1100	connected to dampers	6	20	M30	M10@	190.00

Table A-0-29 Model (DUC) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	550	CORNER	4	12	M20	M10@	124
13	550	CORNER	4	12	M20	M10@	124
12	600	CORNER	4	16	M20	M10@	100
11	600	CORNER	4	16	M20	M10@	100
10	600	CORNER	4	16	M20	M10@	100
9	650	CORNER	5	16	M20	M10@	113
8	650	CORNER	5	16	M20	M10@	113
7	650	CORNER	5	16	M20	M10@	113
6	700	CORNER	6	16	M20	M10@	125
5	700	CORNER	6	16	M20	M10@	125
4	700	CORNER	4	12	M25	M10@	166
3	750	CORNER	4	12	M25	M10@	183
2	750	CORNER	4	12	M25	M10@	183
1	750	CORNER	4	12	M25	M10@	183

Table A-0-30 Model (DUC) external columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	600	EXTERNAL	4	16	M20	M10@	100
13	600	EXTERNAL	4	16	M20	M10@	100
12	650	EXTERNAL	5	16	M20	M10@	113
11	650	EXTERNAL	5	16	M20	M10@	113
10	650	EXTERNAL	5	16	M20	M10@	113
9	700	EXTERNAL	4	12	M25	M10@	166
8	700	EXTERNAL	4	12	M25	M10@	166
7	750	EXTERNAL	4	12	M25	M10@	183
6	750	EXTERNAL	4	12	M25	M10@	183
5	750	EXTERNAL	4	12	M25	M10@	183
4	750	EXTERNAL	4	16	M25	M10@	131
3	800	EXTERNAL	5	16	M25	M10@	143
2	800	EXTERNAL	5	16	M25	M10@	143
1	800	EXTERNAL	5	16	M25	M10@	143

Table A-0-31 Model (DUC) internal columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	650	INTERNAL	5	16	M20	M10@	113
13	650	INTERNAL	5	16	M20	M10@	113
12	700	INTERNAL	6	16	M20	M10@	125
11	700	INTERNAL	4	12	M25	M10@	166

10	700	INTERNAL	4	12	M25	M10@	166
9	800	INTERNAL	5	12	M25	M10@	143
8	800	INTERNAL	5	16	M25	M10@	143
7	800	INTERNAL	5	16	M25	M10@	143
6	850	INTERNAL	5	16	M25	M10@	156
5	850	INTERNAL	4	12	M30	M10@	210
4	850	INTERNAL	4	12	M30	M10@	210
3	900	INTERNAL	4	12	M30	M10@	226
2	900	INTERNAL	4	16	M30	M10@	162
1	1000	INTERNAL	5	16	M30	M10@	187

Table A-0-32 Model (DUC-D) corner columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	450	CORNER	4	0	M15	M10@	95
13	450	CORNER	4	0	M15	M10@	95
12	500	CORNER	5	16	M15	M10@	80
11	500	CORNER	5	16	M15	M10@	80
10	500	CORNER	5	16	M15	M10@	80
9	550	CORNER	5	16	M15	M10@	92
8	550	CORNER	5	20	M15	M10@	92
7	550	CORNER	5	0	M15	M10@	92
6	600	CORNER	6	0	M15	M10@	81
5	600	CORNER	6	0	M15	M10@	81
4	600	CORNER	6	20	M15	M10@	81
3	650	CORNER	7	24	M15	M10@	73
2	650	CORNER	7	24	M15	M10@	73

1	650	CORNER	7	24	M15	M10@	73

Table A-0-33 Model (DUC-D) external columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	500	external	5	24	M15	M10@	80
13	500	external	5	16	M15	M10@	80
12	550	external	5	16	M15	M10@	92
11	550	external	5	16	M15	M10@	92
10	550	external	5	20	M15	M10@	92
9	600	external	6	20	M15	M10@	81
8	600	external	6	0	M15	M10@	81
7	650	external	7	0	M15	M10@	73
6	650	external	7	24	M15	M10@	73
5	650	external	7	24	M15	M10@	73
4	650	external	7	24	M15	M10@	73
3	700	external	6	20	M20	M10@	97
2	700	external	6	0	M20	M10@	97
1	700	external	6	0	M20	M10@	97

Table A-0-34 Model (DUC-D) internal columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	550	internal	5	16	M15	M10@	92
13	550	internal	5	16	M15	M10@	92
12	600	internal	6	24	M15	M10@	81

11	600	internal	6	20	M15	M10@	81
10	600	internal	6	20	M15	M10@	81
9	700	internal	6	0	M20	M10@	97
8	700	internal	6	20	M20	M10@	97
7	700	internal	6	20	M20	M10@	97
6	750	internal	6	20	M20	M10@	107
5	750	internal	6	20	M20	M10@	107
4	750	internal	6	0	M20	M10@	107
3	800	internal	7	0	M20	M10@	94
2	800	internal	5	0	M25	M10@	143
1	850	internal	5	16	M25	M10@	156

Table A-0-35 Model (DUC-D) internal connected to dampers columns reinforcement

			FLEXURAL REINFORCMENT			SHEAR REINFORCMENT	
Story	Section B=H (mm)	locations	# LAYERS	#bars	rebar's size	Stirrups	Spacing (mm)
14	550	connected to dampers	5	16	M15	M10@	92
13	550	connected to dampers	5	16	M15	M10@	92
12	600	connected to dampers	6	20	M15	M10@	81
11	600	connected to dampers	6	20	M15	M10@	81
10	600	connected to dampers	6	20	M15	M10@	81
9	700	connected to dampers	6	20	M20	M10@	97
8	700	connected to dampers	6	20	M20	M10@	97
7	700	connected to dampers	6	20	M20	M10@	97
6	750	connected to dampers	6	0	M20	M10@	107
5	750	connected to dampers	6	0	M20	M10@	107
4	750	connected to dampers	6	0	M20	M10@	107

3	800	connected to dampers	7	24	M20	M10@	94
2	800	connected to dampers	5	16	M25	M10@	143
1	850	connected to dampers	5	20	M25	M10@	156