SOFTWARE DEVELOPMENT FOR

R/C BUILDING VULNERABILITY INDEX

AND

MEMBER IMPORTANCE CALCULATION

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ABSTRACT

SOFTWARE DEVELOPMENT FOR R/C BUILDING VULNERABILITY INDEX AND MEMBER IMPORTANCE CALCULATION

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Turkey has many active faults which have the potential to generate large earthquakes. Recent earthquakes showed that the buildings in Turkey are not well designed and vulnerable to earthquakes. Previous studies on the subject showed that many structures in Turkey need to be strengthened before the next major earthquake to minimize property loss and casualties.

A number of fast and approximate (mostly empirical) methods have been developed in the past to process large building stock. However, there are some important and special structures that do not fit with the general building stock and needs special consideration (e.g., disaster management center, governmental buildings, hospitals, tall structures, etc.). This study targets to evaluate those important and special structures in a detailed, fast, and correct manner. The developed software, which constitutes an important part of this study, does process the building information several times to determine member-based importance factors. The vulnerability index of the building will be determined using the importance of each load-carrying member and how much each member is forced with respect to its capacity.

In order to augment user perception, a functional graphical user-interface is designed. Software is equipped with modules that generate input files for SAP2000 analysis program, conduct dynamic and static analysis automatically, and post-process the generated analysis results which enable the engineer to make a decision on the vulnerability of the structure. Program is written in C++, using object-oriented programming technique.

The main difference between this and similar studies is the generator program which automatically generates 3D-FE models and post-processes non-linear analysis results for an effective decision mechanism. In this way, more realistic results can be obtained much faster.

As future studies, new routines are planned to be implemented to the graphical user interface of the program which will suggest smart and engineered retrofit/strengthening alternatives to the user.

Keywords: Earthquake, Vulnerability Assessment, Member Importance, Pushover Analysis

ÖZ

BETONARME BİNALARIN HASAR İNDEKSİ VE ELEMAN ÖNEM KATSAYILARININ HESAPLANMASI İÇİN PROGRAM YAZILMASI

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Türkiye aktif faylarin bulundugu bir bölgede yer almaktadır. Son yıllarda yaşanan depremler, yapılarımızda depreme karşı dayanım eksikliğinin ne kadar ciddi boyutlarda olduğunu açık bir şekilde ortaya koymuştur. Deprem konusunda yürütülen calışmalar, ülkemizde güçlendirilmesi gereken halen birçok bina oldugunu göstermektedir. Yapısal olarak depreme dayanıksız binaların tespit edilmesi ve zayıflık derecelerinin belirlenmesi ile ilgili birçok çalışma yürütülmektedir. Bu binaların yeni depremler öncesinde güçlendirilmesi, can ve mal kaybını engellemek için atılması gereken ilk adımı oluşturmaktadır.

Değerlendirilecek yapı stoğunun çok büyük olması sebebiyle yaklaşık ve hızlı (emprik) değerlendirme metodları geliştirilmiştir. Fakat, önemi büyük ve değerli binaların (afet merkezi, devlet binaları, hastane, yüksek yapılar vb.) değerlendirilmesi, genel yapı stoğu ile uyuşmamaktadır, özel ve daha detaylı çalışmalar gerektirmektedir. Yaptığımız çalışma, yukarıda ifade edilen detaylı analiz ve değerlendirmenin hızlı ve doğru bir şekilde yapılmasını amaçlamaktadır.

Bu çalışmanin önemli bir parçası olan software, yapılar hakkında toplanan verileri hızlı, doğru ve otomatik olarak defalarca işleyebilecek ve binalar için eleman bazında detaylı zayıflık ve risk analizi yapabilecektir. Binanın toplam deprem zayıflığını gösteren katsayı, her taşıyıcı elemanın sistemin bütünlüğü içindeki öneminin ve sistem yüklemelerinde ne kadar zorlandığının bileşkesi olarak hesaplanacaktır.

Kullanıcı algısını artırmak amacı ile, yapının hızlı bir şekilde modellenmesini, analiz motoru olarak kullanılan Sap2000 programına girdi dosyası oluşturulmasını, gerekli statik ve dinamik analizlerin otomatik olarak yapılmasını ve sonuçların değerlendirilerek yapı hakkında karar verebilmek için gerekli bilgilerin kullanıcıya sunulmasını sağlayan fonksiyonel bir grafiksel kullanıcı ara-yüzü ve pogram motoru tasarlanmıştır. Program C++ dili ile nesne tabanlı olarak yazılmıştır.

Bu çalışmayı benzer konuda yapılan çalışmalardan ayıran en büyük fark yapının üç boyutlu geometrik özelliklerinin otomatik olarak oluşturulmasını sağlayan motora sahip olması ve doğrusal olmayan analiz tekniklerinin effektif olarak kullanılarak sonuca gidilmesidir. Bu sayede daha gerçekci sonuçlara daha hızlı bir şekilde ulaşma imkani doğacaktır.

Gelecek çalışmalar, programa eklenecek yeni modüller aracılığı ile hasar riski fazla olan binalarda yapılabilecek güçlendirme çalışmaları ile ilgili önerileri de içerecektir.

Anahtar Kelimeler: Deprem, Yapı hasar riski analizi, Eleman önem katsayısı, İtme Analizi

To my dear parents, Nahide and Mehmet Ali Öksüz…

To my dear brother Mehmet Öksüz…

To Iraz Yaşar who gave great support…

with all my heart…

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A_{sw22} : Total transverse reinforcement area in 2-2 direction

A_{sw33} : Total transverse reinforcement area in 3-3 direction

A_e : Area enclosed by shear flow path of a section

A_{to} : Cross-section area of hoop steel

A_{ch} : Gross section area of shear wall

d_{22} : Depth of section parallel to 2-2 direction

d_{33} : Depth of section parallel to 3-3 direction

b_{w22} : Width of section perpendicular to 2-2 direction

b_{w33} : Width of section perpendicular to 3-3 direction

f_{ywk} : Yield strength of transverse reinforcement

f_y : Yield strength of longitudinal reinforcement

f_{ct} : Tensile strength of concrete

f_{ck} : Compressive strength of Concrete

V_r : Shear capacity of section

V_w : Contribution transverse reinforcement to shear capacity of section

V_c : Contribution of concrete to shear capacity of section

V_{r22} : Shear capacity of section in 2-2 direction

V_{r33} : Shear capacity of section in 3-3 direction

ρ_n : Ratio of horizontal web reinforcement of wall to the gross area of wall web

CHAPTER 1

INTRODUCTION & LITERATURE SURVEY

1.1 INTRODUCTION

There are numerous studies all around the world about earthquake vulnerability assessment of R/C buildings. These studies are widely carried out in countries located on seismically active zones, as Turkey. The recent earthquakes have also shown the importance of such studies to detect vulnerabilities for structural behavior improvement of R/C buildings.

Turkey is located on a zone with high earthquake risk. It is a fact that over 90% of the population in Turkey is living on seismically active zones. Last three major earthquakes caused serious damages and death toll of over 20000 citizens. It is also known that those earthquakes were not the last ones. To avoid recurrence of similar scenes, detailed vulnerability assessments and related building rehabilitation studies should be carried out.

Majority of the current seismic vulnerability assessment approaches are based on statistical methods applied on data collected from a number of recent earthquakes and observed structural damages. These techniques have 3 main steps for structural evaluation. These are:

1. Walk down study
2. Preliminary study
3. Final study

Walk down study

Seismic vulnerability assessment of a building stock for an expected earthquake is a very big project, which requires extensive time and effort. If possible, to categorize buildings according to their seismic performance without doing detailed analyses can simplify the determination of priority levels of the buildings in a zone. This is the first step, which is fast and quite valuable. A slightly qualified engineer can participate in this step, which requires the use of an evaluation sheet and information regarding past experiences. The performance level and performance score of the building is obtained after the evaluation of the information observed. This score is used to determine the priority level of the building. The buildings, which have low scores, as far as their performance levels are considered, should be evaluated further. This step is also used in American and Japan assessment procedures.

Preliminary Study

After quick evaluation of the buildings in walk down study step, the buildings, which have inadequate performance, are evaluated in "Preliminary Study" step. In this step simplified structural analyses are conducted, therefore sufficient information about the building must be provided.

Final Study

The buildings, which are categorized as risky in the first two steps, are studied further. This step includes detailed seismic analyses of the building according to the current earthquake code. It is a must that an experienced engineer should be included in this step. The decision given about the building in this step determines the future of the building. After this step, strengthening and rehabilitation studies are conducted, if required.

If three steps are conducted for a building, the evaluation procedure takes one to several weeks.

Today, most commonly used techniques are developed to obtain more reliable results and to reduce the time required for the evaluation in first and second steps. These assessment procedures use building layout and structural member properties to predict the vulnerability score of the buildings and they give successful results to some extent. In these procedures the results of the studies are evaluated without realizing the real structural behavior of the building due to lack of time and the engineer is not fully included to act as a comment center. And it is well known that each building has its own distinct seismic behavior, which can be realized to a certain level by use of static and dynamic analyses. Therefore the evaluation done on different buildings, which have same variables to be used in statistical methods, leads to same vulnerability level, although their real behaviors are different. Most of the statistical procedures can not recognize the consequences of building behavior differences on vulnerability.

The aim of this study is to bring new methodology for the evaluation of the member importance in R/C buildings. Structural properties of the buildings are taken as basic inputs, which means engineer will have chance to decide on the seismic performance of the building based on the analytical behavior of the building. The developed software for this study, CAVAS, is a step to determine the overall performance level of buildings based on the importance factors computed for each member in a building.

In order to get more realistic results, it is required to work using a 3D analysis tool. In this study SAP2000 is chosen as the tool to be used as a *static analysis subroutine*. SAP2000 works as if it is a function of the developed software, which will be explained in detail in the Chapter 2. At each step of the developed program execution, SAP2000 analysis outputs are used as the inputs for specific implemented functions, which have ability to evaluate the results. A detailed pushover procedure is implemented in the software using numerous functions SAP2000. This procedure is solely developed by the author of the thesis for this specific topic.

1.2 SCOPE OF THE STUDY

The scope of this study is summarized as follows:

- To write 3D-FE model generator.

  This module is implemented to construct the model of a building, which can be imported to SAP2000 directly. Developed software uses more simplified input file to construct more complicated SAP2000 input file.

- To implement an "Input Module" to be used with building database.

  With this module the results of the analyses and evaluations can be stored. Stored information can be used in further evaluation steps.

- To write "Pushover Module" (Automatically applied to the building) which uses SAP2000 as a static analysis function.

  This module is specially implemented for this study and it is capable to do pushover analyses with options that can be modified according to the requirements. This module gives flexibility to the engineer to study the behavior of buildings for different situations. Also step-by-step damages on the building can be figured out. This option is a step for *Sequential Collapse* topic.

- To write 3D-FEM Based "Vulnerability Index Calculation Module".

  This module is implemented to find out importance of members in the building, which is the first step in seismic vulnerability evaluation of buildings.

- To test software with four different buildings

  Four different buildings are tested and the discussion on the results is presented.

1.3 OBJECTIVES OF THE STUDY

The objectives of this study are summarized as follows:

- Vulnerability assessment procedures generally includes three main step:
    - Walk down study
    - Preliminary study
    - Final study

  With the implemented software it is aimed to combine first and third steps and reduce the time required for the detailed analyses. As soon as the layout of the building is introduced with reinforcement data to the software, final step analyses can be performed immediately.

- In this study it is aimed to include dynamic behavior of the buildings as basic criteria besides member and building geometric properties. This is an improvement for the current seismic vulnerability assessments. Indeed, geometric properties of the buildings, which have been used in statistical approaches, are also included this study, because the original building is evaluated with all properties.

- Implemented SAP2000 input generator module in the software reduces time required to model the building and provides different options for an engineer who wants to conduct different analyses on the building.

- Developed software is a tool that serves as streamline between FE Model generation, related analysis and post-processing work.

- The software can evaluate building database directly on condition that the stored building information is in proper format. With this facility it is possible to evaluate all the buildings in the stock one by one automatically.

The general layout of the study is summarized as follows:

In Chapter 1, general information about the study and scope is given. The objectives of the study and brief information about previous studies conducted in the area of seismic vulnerability are also presented. In Chapter 2, detailed information about general four main modules of the software is presented and implemented pushover procedure is explained in detail. Chapter 3 completely involves section capacity calculation procedures and implemented member behaviors. The attributes defined in this chapter constitute the basis of pushover analysis. In Chapter 4, after brief definition about C++, which is the object oriented programming language that is used in coding, explanations of the implemented classes are presented. The user interface and related options are also explained in this chapter. Chapter 5 involves the verification of software and example evaluation procedures conducted on four buildings. The proposed method with this study is explained in details with the applications demonstrated in this chapter. In Chapter 6, vulnerability index computation methodology is explained and application of the procedure is demonstrated with an example building. Chapter 7 includes the summary of the study and conclusions. In Appendix A, implemented failure simulation procedure, which is also called *Sequential Collapse,* is explained with main assumptions made. Procedure is applied on an example building and failure steps are demonstrated. In Appendix B verification of the CAVAS software is conducted using commercially available analysis software SAP2000 and of the results are presented.

1.4 REVIEW OF PREVIOUS STUDIES

The attributes of *Seismic Vulnerability Assessment* studies vary for different regions and for different construction methods. However, their objectives are common: To evaluate buildings to find out their seismic vulnerabilities. Different techniques in this area are briefly explained in this section.

1.4.1 Seismic Vulnerability Assessment Used in USA [1, 2, 3]

The method is developed by ATC to evaluate buildings according to their seismic performances in a fast and easy way. This method has a step by step evaluation scheme. Each new step requires more detailed information about the building. The steps are as follows:

1. Rapid Visual Screening
2. Detailed Evaluation
3. Engineering Evaluation

If the seismic performance and safety level of the building is found to be adequate at any of the above mentioned steps, the evaluation might be immediately finalized. The description of each step is as follows:

1.4.1.1 Rapid Visual Screening

As the name of the step implies, this step is rapid and easy to apply. In this step simply a site survey is conducted to get rough information about the buildings to be evaluated. Here the aim is to sort out buildings, which might have serious damage during a possible earthquake. The scoring of the building is done based on structural score and performance modifier scores. The structural hazard score for twelve different building types are presented in FEMA 154 [1]. The performance modifier scores are used to represent the deficiencies on the building, as lack of material quality, openings, short columns, floor torsion, pounding effect, irregularities in plan and elevation etc. Scoring system for the above mentioned deficiencies changes according to the ground motion expected. This branching provides refinement in the evaluation. In this step, the final score for the building is computed by subtracting scores obtained for the above mentioned deficiencies from the basic hazard score. Low score indicates the degree of incapability of the building to resist.

1.4.1.2 Detailed Evaluation

This step is conducted to find out deficiencies of the buildings which might yield to failure. The deficiencies indicated here are determined by some simple analyses. Lateral load capacity of a building is evaluated by shear and drift computations. Shear check is conducted by computing shear capacities of columns and shear walls, whereas drift check is based on determination of story drifts by use of relative rigidity of frame elements. In this step additional information is collected based on the replies to a set of questions. The questions vary for 15 types of buildings which are given in FEMA-178 [2]. The contents of the questions are as follows:

- Regarding Building System: weak story, vertical discontinuities, pounding, torsion, etc.
- Regarding Diaphragms: Plan irregularities, openings, spans, reinforcements at openings, etc.
- Regarding Connections: Connection details of column and shear wall bases with foundation, etc.

1.4.1.3 Engineering Evaluation

If the decision is not positive at previous steps, more detailed evaluation procedure is conducted and final decision about the building performance is given. An experienced engineer must be included for analyses and evaluation at this step. Nonlinear static and dynamic analyses are conducted. The design requirements are checked with the latest design code. Through out this step, FEMA 273 [3] is taken as guideline for evaluation.

1.4.2 Seismic Vulnerability Assessment Used in JAPAN [4,5,14]

In Japan, the "Allowable Stress Design" recommendations have been used for many years. Therefore, big columns and shear walls are commonly used in the designs to meet high lateral seismic loads. In Japan, the reason of using big members is the presence of high earthquake risk. For the buildings in Japan the deformation capacity estimation is a hard task. To overcome this problem, Ohkuba [4] and Otani [5] proposed a method based on the strength capacity estimation of the buildings. This method is used to evaluate seismic capacity of buildings and to estimate their seismic vulnerability. The details of this evaluation system are described in standard titled "The Standard and Commentary for Evaluation of Seismic Capacity of Existing R/C Buildings" [14]. Proposed method is applicable to the buildings with up to six stories and has mainly 3 steps, which comprises different evaluation processes and structural indices. In all steps, the computed indices are compared with the seismic performance index to give a decision about the vulnerability the building for that step. Three steps are described as follows:

1.4.2.1 1st Level Screening

The aim in this step is to sort out buildings which can resist earthquakes without any ductility requirement. Lateral load strength of the building is computed using cross-section areas of columns and shear walls and their shear capacities. In this step the resistances of beams are not considered during the analyses and only shear walls and columns are considered as members to resist applied lateral loads.

1.4.2.2 2nd Level Screening

For the buildings which are determined as vulnerable in the first step, the procedure proposed for the second step is conducted. Failure mechanism of the building is evaluated by considering shear wall and column strength and ductility attributes. The resistance of the beams is ignored as in the first step. The failure mechanism found in this step constitutes the basis of the seismic vulnerability evaluation for the building.

1.4.2.3 3rd Level Screening

This is the last step where the final decision about the building is given. To give precise decision, all possible failure mechanisms are studied in detail. In the conducted analyses, hinging of beams, shear failures, torsional behavior of columns and shear walls are also considered. The vulnerability index found at the end of conducted analyses is used as the concluding decision about seismic performance of the studied building.

1.4.3 Previous Studies Conducted in Turkey

In this section brief explanations of the related past studies conducted in Turkey in the area of seismic vulnerability assessment for reinforced concrete buildings are given.

1.4.3.1 Hassan and Sozen [10]

The method proposed by Hassan and Sozen [10] is applicable for seismic vulnerability assessment of low-rise monolithic buildings. The objective of this simplified method is to predict and identify the buildings which might be exposed to severe damage during an expected earthquake. In ranking, geometric properties of members and geometric properties of the buildings are used. In the proposed method, summation of column and wall indices gives "Priority Index" which is used to categorize buildings. Lower the "Priority Index", higher the earthquake risk. The wall index is defined as ratio of total effective cross-sectional area of walls to the total floor area above base level, and column index is defined as the ratio of effective total cross-sectional area of columns to the total floor area above base level.

The validity of the method has been tested by the authors with the data collected for buildings after 1992 Erzincan earthquake with wide rank of damage levels and the results were found to be satisfactory.

1.4.3.2 Gulkan and Sozen [9]

The method proposed by Gulkan and Sozen [9] is applicable for seismic vulnerability assessment of reinforced concrete frames with masonry infill walls. This method can not be applied to the systems with shear walls because of the basic assumption used to define deflected shape of the frames.

The basic parameters used for this method are column ratio, which is defined as the ratio of cross-sectional areas of columns to the total floor area in a given direction at base level, wall ratio, which is defined as the ratio of effective cross-sectional areas of infill walls to the total floor area in a given direction at base level, number of stories, unit mass of the building, storey heights, column slenderness ratios.

In this method additionally drift check formulation is proposed, which relates ground storey drift with vulnerability of the building. High level of ground storey drift indicates high seismic vulnerability.

The validity of the method has been tested by the authors with the data collected for buildings after 1992 Erzincan earthquake with wide rank of damage levels and the results were found to be satisfactory.

1.4.3.3 Ersoy and Tankut [11]

Ersoy and Tankut [11] proposed a method to evaluate seismic design of low-rise residential reinforced concrete buildings. The method is based on the collected data from Erzincan and Dinar earthquakes. Some of the observations are as follows:

- To have earthquake resistance, sufficient lateral strength and stiffness should be provided. Without ductility requirement, the buildings with adequate lateral strength showed reasonable seismic performance.
- Masonry walls have considerable effect on the seismic performance of the buildings.

- For the buildings which are constructed properly with the guideline of "Specifications for Buildings to be built in Disaster Areas", detailed analyses are not required.
- The buildings that satisfy below mentioned equations in both directions, behave satisfactorily under earthquakes.

$$\left(k.\sum A_c + \sum A_w\right) \geq 0.003 \cdot \sum A_p \tag{1.1}$$

$$\sum A_w \geq 0.002 \cdot \sum A_p \geq 0.01 A_{pb} \tag{1.2}$$

A_c : Column area

A_w : Wall area

$\sum A_p$: Total Floor area above base level

A_{pb} : Floor area at the base level

k : 1/2 for square and circular columns

1/3 for rectangular columns in their shorter direction

2/3 for rectangular columns in their longer direction

The ratios of column and shear wall areas to the required area, which is defined with the above equations, are calculated for each direction. The smaller of the ratios is used during evaluation with the below mentioned criteria:

- If ratio is much larger than 1.0, no severe damage is expected during an earthquake.
- If ratio is much smaller than 1.0, severe damage is expected during an earthquake.

The validity of the method has been tested by the authors with the data collected for buildings after 1992 Erzincan earthquake with wide rank of damage levels and the results were found to be satisfactory.

1.4.3.4 Pay [6]

Pay [6] proposed a method which is based on discriminate analysis technique a for seismic vulnerability assessment of existing reinforced concrete buildings in Turkey. The parameters used in the analyses are:

- Number of stories.
- Soft story.
- Overhang ratio.
- Redundancy.
- Square root of sum of squared moment of inertias.

The method was applied to buildings which have been damaged in recent earthquakes. The results showed that two parameters which are "overhang ratio" and "soft story", do not have significant effect for the evaluation procedure. These two parameters are excluded from the method. With the final formation of the method, the statistical evaluations have been performed with remaining three parameters.

The evaluations have been conducted for two damage state definitions:

1. This definition includes two performance levels which are:
    - Life safety performance level
    - Immediate occupancy performance level
2. This definition includes four damage states

The validity of the method has been tested with the damage database prepared for Düzce-Bolu-Kaynaşlı zone with wide rank of damage levels and the results were found to be satisfactory.

1.4.3.5 Aydogan [8]

Aydogan [8] proposed a statistical model for the preliminary seismic vulnerability assessment of low to mid rise existing reinforced concrete buildings by using multivariate statistical procedure, called discriminant analysis.

With the proposed model following parameters are selected as the basic estimation parameters:

- Number of stories.
- Minimum normalized lateral stiffness index.
- Minimum normalized lateral strength index.
- Normalized redundancy score.
- Soft story index.
- Overhang ratio.

Analyses are conducted in two stages. And then, optimal classification methodology was developed for the conducted two stage analyses to improve the classification rates.

The validity of the method has been tested with the damage database prepared for Erzincan and Afyon zone with wide rank of damage levels and the results were found to be satisfactory.

CHAPTER 2

MODEL GENERATOR AND ANALYSIS SOFTWARE

2.1 INTRODUCTION

To fulfill the requirements of this study, software “CAVAS” is developed and used. In this chapter the properties of the software is presented. Software capabilities, general layout of the software, step by step program flow and assumptions made are described.

2.2 SOFTWARE CAPABILITIES

The software is basically composed of four modules:

i. Pre-processor
ii. Central-processor
iii. Post-processor
iv. Importance Evaluation Module

Among above mentioned modules, the *Pre-processor* and *Importance Evaluation Module* are independent from other two modules in the general layout of the software. *Pre-processor* module is called at the beginning of each analysis to prepare detailed information regarding the building to be used with other modules. But *Central-processor* and *Post-processor* are working together through out the program flow. There is cycling relation between these modules. *Importance Evaluation Module* is called after the analyses are completed. Importance of each member is determined with this module.

The details of the modules are described as follows:

2.2.1 Pre-Processor

Besides *Vulnerability Index Calculation* issue, one of the other objectives aimed with CAVAS is to facilitate input preparation for SAP2000. There are two major reasons for implementing a module which evaluates a separate input file specific for the software, instead of using SAP2000 input file format:

i. To give programmer more control over the building model.
Details of this item are related with programming issues, which will be explained in Chapter 4.

ii. To simplify overall process and reduce time required to generate model.

In general, when an engineer works on a building, the main issues to be concentrated must be structure and its behavior. Modeling of the structures is generally time consuming issue. Especially, with general purpose FE software, this process gets harder and harder. At this point the idea of simplified input file format, specifically designed for building type structures comes into scene. This simplified input format helps the engineer to generate models in SAP2000 faster and in reliable manner. As the basic items used in the simplified input file are described further, the easiness of this process will be more clear. The flowchart for *Pre-Processor* is given in Figure 2.1.

The basic inputs, which are used in modeling a structure, are explained briefly as follows:

i. Two different floor plan concept :

It is assumed that, in a building there exist no more than two different floor plans. These plans are for first floor (base level layout) and for the remaining floors (generally because of extensions in floor plan). If the building has only one floor plan, additional floor input details are not required by the software. If two different floor plans are used, in second floor plan definition, first floor plan layout is kept and additional plan details are added. As far as the general building plans are considered, the validity of this approach is verified.

ii. Floor Replication:

Another basic input is the number of floors in a building. After floor plans are defined, number of storey information is sufficient to define all floors through the height of the building. With the replication of floors, all the members that constitute the building (shear walls, beams, columns and shells) are also replicated.

iii. Diaphragm Behavior:

Generally, the floors are assumed to show diaphragm behavior. Diaphragm behavior ensures that all of floor nodes to move together as a planar diaphragm. This can be achieved by defining floor diaphragms for each floor or by defining shell elements through all floors. In the software, shell modeling technique is chosen to simulate diaphragm behavior. Shell generation process is implemented automatically by the software. The thickness of the shell element is sufficient data to model all shell elements through the building. The number of meshed shells in closed regions, which are called as *parcel*, is determined with the number of beams in each interconnected parcels. The advantages of shell implementation are as follows:

- To facilitate distribution of dead loads automatically.
- To be used in module which is designed to simulate sequential collapse scheme, described in Appendix A.

iv. Member Labeling Facility:

The pre-processor has its own naming convention, which makes it easier to figure out the location of members or joints. This helps engineer to study any member at any location without having needed to see the plan of the building.

v. Loading Cases:

The loadings applied to the structure are also handled by the software. There are two loading types:

- Dead Load.
- Pushover Displacement Loads.

Dead load is cumulative of self-weight of members and floors. Self weights of floors are distributed along the beams, proportional with their lengths. Pushover displacement loads are assigned to each node of the building based on relative drift of each node with respect to observation node, calculated with the mode shape at each step. Details of this topic are given in section 2.2.2.1.13.

Besides simplifications in modeling of floor plans and load definitions, another facility come with the input file format is easy definition of member reinforcement details. Reinforcement definitions for columns, beams and shear walls are same and designed to be as practical as possible. Reinforcement data are used in generation procedures of *Moment-Curvature* and *Interaction Relation*. Before starting analysis of a model, user can obtain and study above mentioned relations easily. In this aspect, software can be used as a tool which computes section properties.

Another easiness that comes with the software is its ability to show all members in a floor in a spreadsheet format. With this facility the sections of the members located on different floors can be revised to get original building layout with correct sections. The generated building can be checked with this facility before starting the analyses.

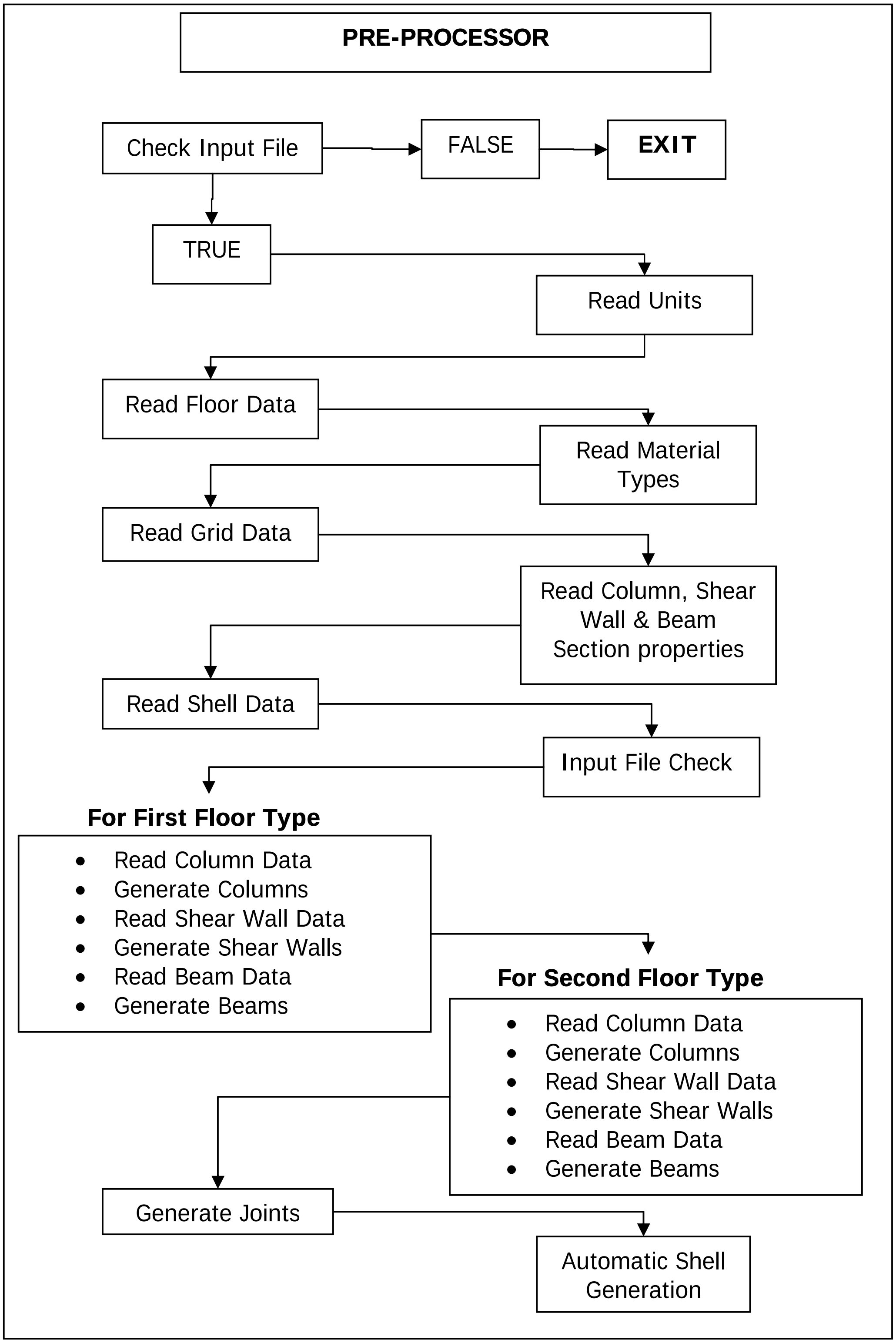

Figure 2.1 Pre-Processor Program Layout

2.2.2 Central-Processor

Pushover analysis is very powerful tool to get information about behavior and energy dissipation capacity of the structure. And energy dissipation capacity of structure and members is one of the main properties that is used in vulnerability index calculation conduced in this study. Central-processor includes number of modules that makes it possible to conduct pushover analysis. The reasons to develop a customized push-over analysis module, instead of using SAP2000 pushover module, are listed below in bullet list format:

- CAVAS gives possibility to direct the pushover analysis according to the aim of engineer. Some of the provided options are as follows:
  - To stop the analysis when specific condition is satisfied.
  - To figure out the effect of the proposed behavior of sections on the overall behavior of the structure.
  - To figure out the effect of proposed behavior of members on the overall behavior of the structure.
- CAVAS gives possibility to collect and display the pushover curves simultaneously which enables comparison of the results and behaviors.
- CAVAS gives possibility to apply multiple pushover analyses continuously.
  This property of CAVAS enables the importance factors of the members to be determined automatically and rapidly.

2.2.2.1 Pushover Procedure

The implemented pushover analysis procedure has an iterative scheme, which includes cycling of built-in procedures. The procedure starts with pushover analysis of original structure. After this procedure is finalized, software starts to remove each of the load carrying members from the structure and continue redoing pushover analysis for each of the modified structure.

The prerequisite of pushover analysis is, input evaluation process to be successfully finalized by Pre-processor. The flowchart of pushover analysis is given in Figures 2.2, 2.3 and 2.4.

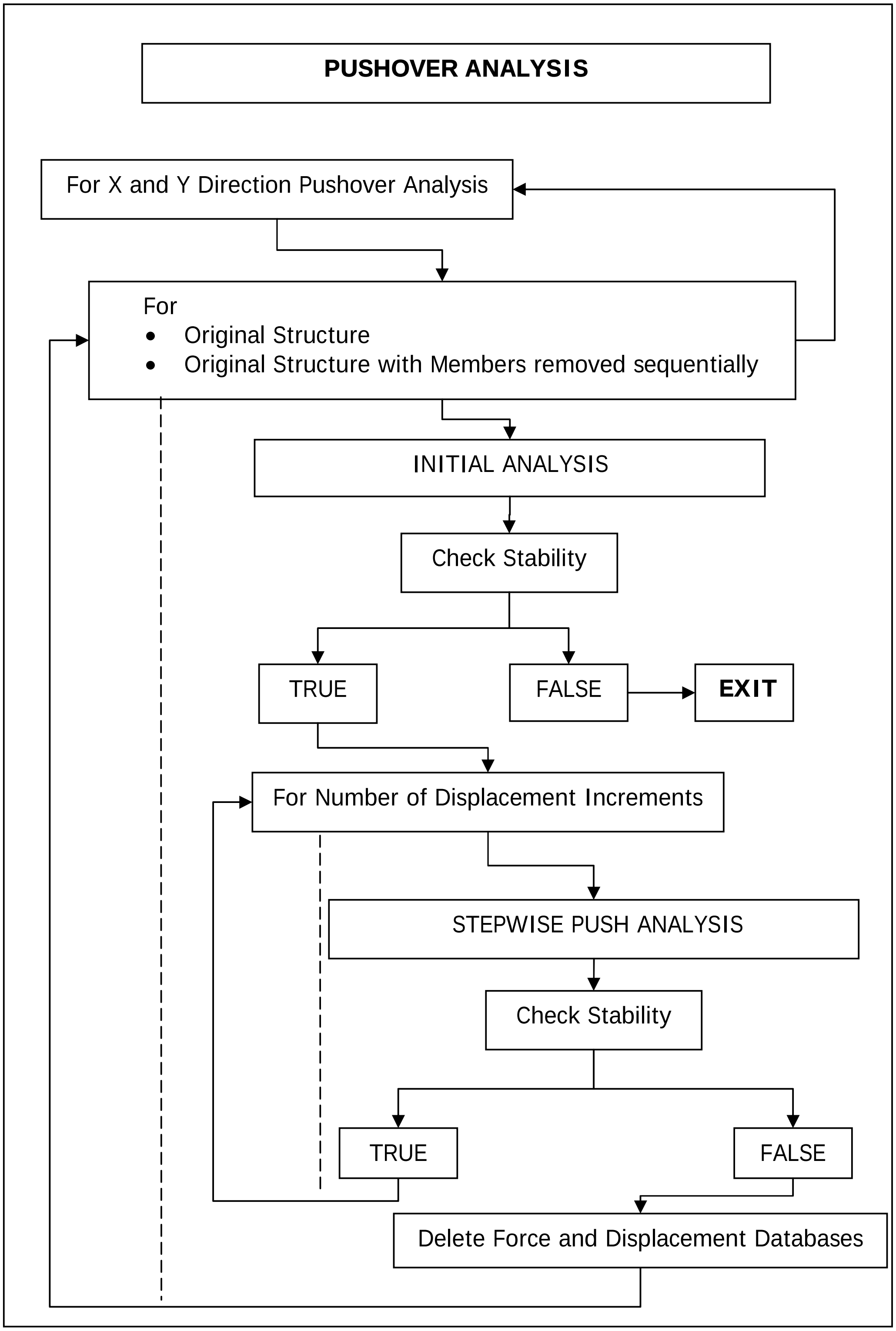

Figure 2.2 Pushover Module Program Layout

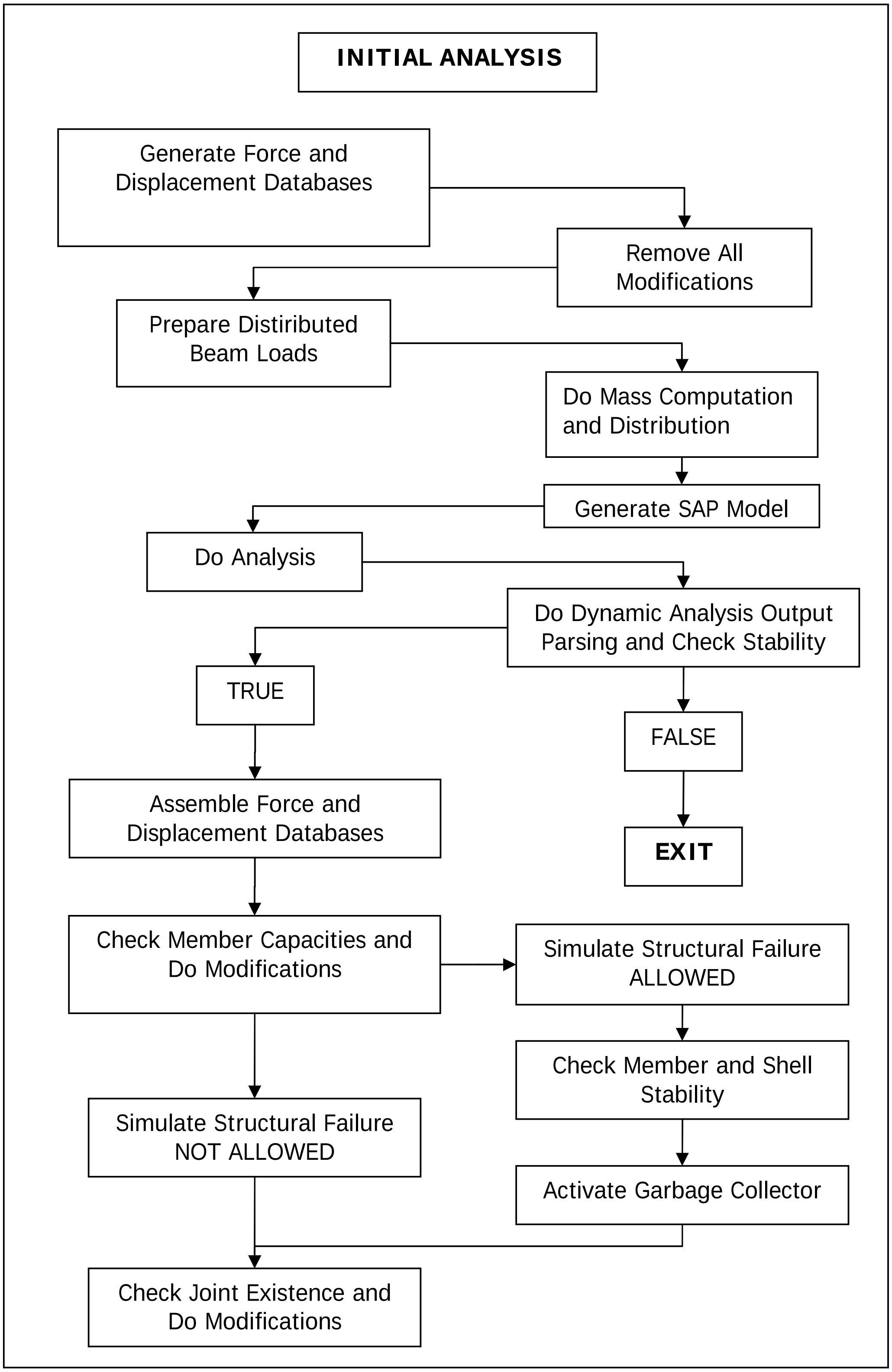

Figure 2.3 “Initial Analysis” Module Program Layout

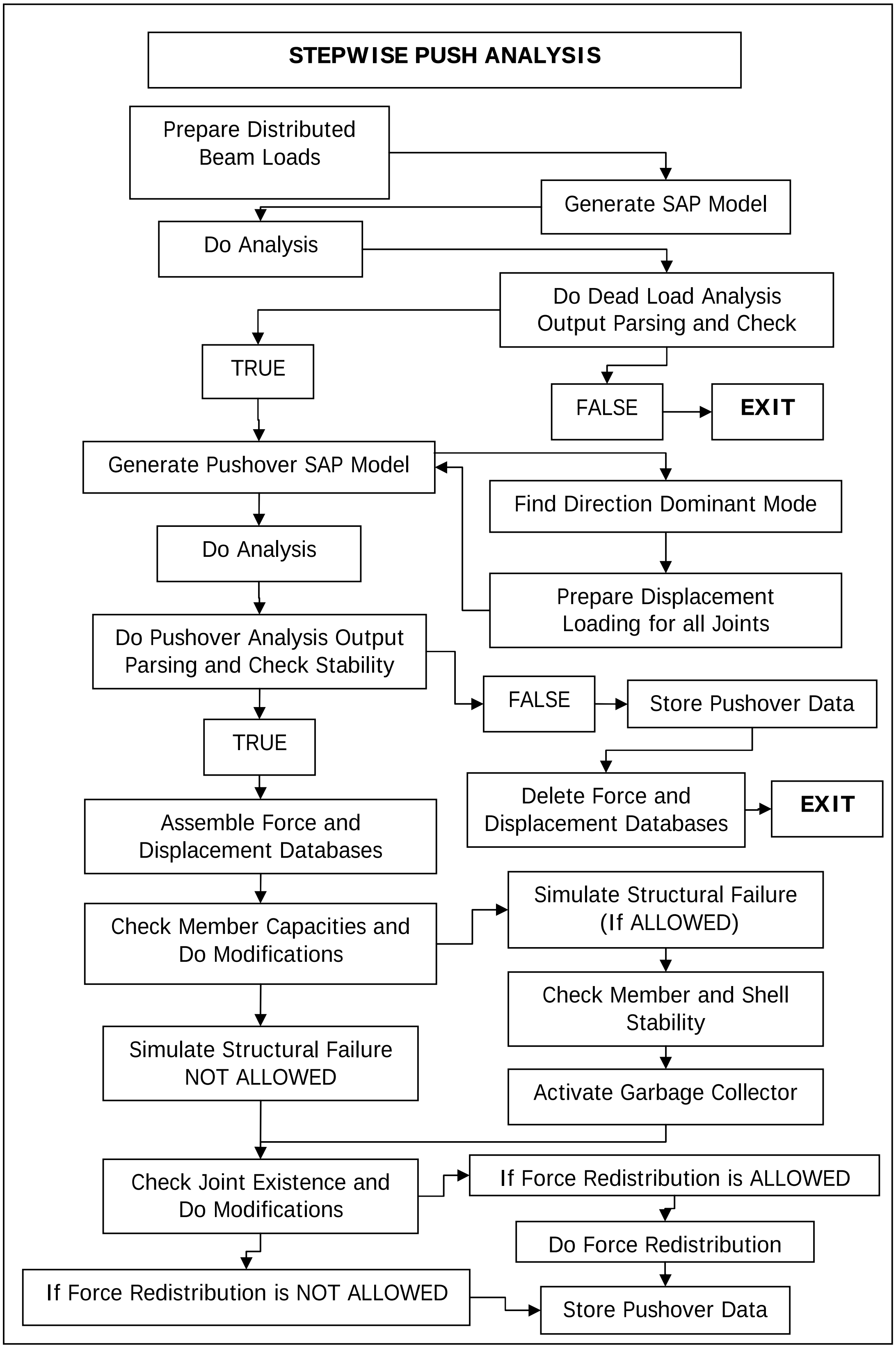

Figure 2.4 "Stepwise Push Analysis" Module Program Layout

The procedures implemented for pushover analysis and their descriptions are as follows:

- Generate Force and Displacement Databases
- Delete Force and Displacement Databases
- Remove All Modifications
- Prepare Beam Distributed Loads
- Do Mass Computation and Distribution
- Generate SAP Model
- Generate Pushover SAP Model
- Do Analysis
- Do Dynamic Analysis Output Parsing and Check Stability
- Do Dead Load Analysis Output Parsing and Check Stability
- Do Pushover Analysis Output Parsing and Check Stability
- Find Direction Dominant Mode
- Prepare Displacement Loading for all Joints
- Assemble Force and Displacement Databases
- Check Member Capacities and Do Modifications
- Check Joint Existence and Do Modifications
- Check Member Capacities and Do Modifications
- Check Member and Shell Stability
- Activate Garbage Collector
- Do Force Redistribution
- Store Pushover Data

2.2.2.1.1 Generate Force and Displacement Databases

To be able to store member end forces and node displacements, arrays of structures defined in “ForceDatabase” and “DisplacementDatabase” classes are generated dynamically. By use of member functions and array operations the values stored are easily controlled. The cumulative force and displacement values are also stored by use of “ForceDatabase” and “DisplacementDatabase” classes.

2.2.2.1.2 Delete Force and Displacement Databases

Sequential pushover analysis requires too many force and displacement values to be stored in memory. When a pushover analysis ends, keeping force and displacement values is unnecessary. Besides, after a few analyses, this bulk of information starts to allocate computer memory considerably. “Delete Force and Displacement Databases” procedure is called as soon as a pushover analysis is finalized to free the memory occupied by the data stored.

2.2.2.1.3 Remove All Modifications

During pushover analyses, some modifications start to take place on the structure. These modifications are due to failure of members or due to formation of plastic hinges at member ends. Applied modifications should be kept through the end of pushover analyses and as analyses continue new modifications should be added at the corresponding locations of the structure. This procedure continues until failure mechanism forms. After pushover analysis finalized, the modifications should be removed, to let other pushover analysis to start properly. “Remove All Modifications” procedure is implemented to remove all modifications done on all the members; columns, beams, shear walls and shells.

2.2.2.1.4 Prepare Beam Distributed Loads

In FE Modeling self weights of all members are distributed over themselves uniformly. But due to model generation procedure implemented for CAVAS, this distribution does not give correct dead load flow, because on generated SAP models, shell member nodes are located over vertical members, which yield floor weights to be directly transmitted to columns and shear walls. In order to simulate real behavior of building, floor weights should be distributed over the beams. “Prepare Beam Distributed Loads” procedure is implemented to distribute floor weights through beams.

2.2.2.1.5 Do Mass Computation and Distribution

Mass computation and distribution issue is important to realize real behavior of the structure and to get correct mode shapes after dynamic analyses. During the evaluation of input file all the members are defined and stored with mass data. Before “Generate SAP Model” procedure is called, “Do Mass Computation and Distribution” procedure is called to gather mass information from all members and distribute them to the nodes. The detailed information about mass computation is given in section 4.3.1.6.

2.2.2.1.6 Generate SAP Model

To start analysis procedure, SAP input file for the building must be generated. With the implemented “Generate SAP Model” procedure, the functions that handle preparation of necessary data blocks for the input file are called. Member function “PrepareSapOutput” of all objects is called within this procedure. The prepared input file is used for dead load analyses and dynamic analyses. Therefore “MASS” and “DISTRIBUTED SPAN” data blocks are prepared only when this procedure is called. Details of “Prepare Beam Distributed Loads” procedure is given in section 2.2.2.1.4.

2.2.2.1.7 Generate Pushover SAP Model

To start pushover analysis procedure, SAP input file with information about pushover data must be generated. With the “Generate Pushover SAP Model” procedure, as “Generate SAP Model” procedure, the functions that handle preparation of necessary data blocks for the input file are called. Member function “PrepareSapOutput” of all objects is called within this procedure. Since the prepared input file is used in pushover analyses, the call for function responsible for the preparation of “RESTRAINT DISPLACEMENT” data block is done with this procedure. The preparation of joint displacement loading is explained in section 2.2.2.1.13.

2.2.2.1.8 Do Analysis

This procedure is implemented to run SAP2000 externally and to remove unnecessary files from the hard disk. After the SAP2000 input file is prepared with any of the previously defined generation procedures, "Do Analysis" procedure is called to start analysis. Analysis is performed by use of two applications provided with SAP2000. After the analysis, numerous files containing information about the analysis results are generated. Except the files with extensions ".s2k" and ".OUT", all remaining files are removed from hard disk. The reason to keep above mentioned two files is to store information about each step of pushover analysis.

2.2.2.1.9 Do Dynamic Analysis Output Parsing and Check Stability

This procedure is implemented to parse corresponding generated output file and to check the stability of the building for the current situation. The file to be parsed must be the output of the analysis performed for the input file generated by "Generate SAP Model". The details of this procedure are explained in sections 2.2.3.1 and 2.2.3.4.

2.2.2.1.10 Do Dead Load Analysis Output Parsing and Check Stability

This procedure is implemented to parse corresponding generated output file and to check the stability of the building for the current situation. The file to be parsed must be the output of the analysis performed for the input file generated by "Generate SAP Model". The details of this procedure are explained in sections 2.2.3.2 and 2.2.3.4.

2.2.2.1.11 Do Pushover Analysis Output Parsing and Check Stability

This procedure is implemented to parse corresponding generated output file and to check the stability of the building for the current situation. The file to be parsed must be the output of the analysis performed for the input file generated by

"Generate Pushover SAP Model". The details of this procedure are explained in sections 2.2.3.3 and 2.2.3.4.

2.2.2.1.12 Find Direction Dominant Mode

This procedure is called by "Generate Pushover Sap Model" procedure, to find out the X and Y dominant modes to be used during analyses. The details of this procedure are explained in section 2.2.3.1.

2.2.2.1.13 Prepare Displacement Loading for all Joints

This procedure is called by "Generate Pushover Sap Model" procedure, to define joint displacements to be applied. In pushover analysis, the building is displaced with the mode shape determined with "Find Direction Dominant Mode" procedure. To force building to displace same as the mode shape, all the joints must be displaced accordingly. To achieve this, for the corresponding mode shape the displacement ratios of all joints, with respect to observation joint is stored. As the displacement of the observation joint is changed, other joints are also forced to displace with the computed amount by use of stored ratios.

2.2.2.1.14 Assemble Force and Displacement Databases

At the end of each step in pushover analyses, the forces and displacements that are stored in different arrays should be assembled in a proper manner. For forces and displacements, the contributions coming from different analyses are stored in different arrays. The reason to store force and displacements contributions separately, even within themselves, is to enable cumulative summation to be performed, simulate redistribution over the structure (this is explained in section 2.2.2.1.17), some options to be implemented like "Include Dead Load Contribution". Cumulative summation procedure is used to generate final structure forces and displacements by adding the current analysis results to the previous cumulative values. At each step, capacity checks are conducted based on cumulative forces.

2.2.2.1.15 Check Member Capacities and Do Modifications

This function activates member capacity check procedure. The details, assumptions made and evaluation procedures for this procedure are described in Chapter 3.

2.2.2.1.16 Check Joint Existence and Do Modifications

This procedure is implemented to remove joints from the model which do not have any connection with a member. During pushover analyses, some modifications start to take place on the structure. One of the modifications performed is, removing member form the structure. When members are removed from the structure, the joints of the member are not removed because existence of a member is not checked during joint generation procedure. The reason of this implementation relies on the fact that one joint can be used in definition of more than one member. To check all joints and remove the ones which are free, “Check Joint Existence and Do Modifications” procedure is implemented. This procedure is called at each time when member capacity check procedure is conducted.

2.2.2.1.17 Do Force Redistribution

“Do Force Redistribution” process is designed to simulate the redistribution of forces at each step of the analyses. Application of this module yields more realistic structural behavior. Theoretically, pushover is forcing structure to displace continuously through a predefined path. But implementation of this process is a very hard issue and also impractical. The practical solution is to push the building by increments and if the increments are chosen small enough, the realistic behavior can be simulated. Even if the increments are small, structural properties can alter within few steps considerably. This module is designed to simulate above mentioned redistribution of forces to increase the reliability of the results.

During pushover analyses, for number displacement increments, none of the members in the structure might have plastic hinges and exposed to shear failure.

But for the next displacement increment, plastic hinges could be formed at some locations. In reality as soon as changes in the structure is observed, redistribution of forces takes place. But since the implemented pushover analysis is a step wise procedure, the redistribution of forces can only be simulated for current increment interval. The steps of this procedure are as follows:

- For a specific displacement value, structural analysis is performed and the results are stored.
- Capacity check procedure is applied for each member.
- Necessary modifications are applied.
  - Placement of member end releases where necessary
  - Removal of the members where necessary
- For the modified structure, analysis is repeated and the results are stored separately.
- The differences between the results of analysis before and after modifications show the effect of the modifications over each member.
- Member forces, reactions and displacements are revised with the difference in results. The revision procedure is described as follows:

Unmodified_Results	= Analysis result for unmodified structure	(2.1)
Modified_Results	= Analysis result for modified structure	(2.2)
Old_Cum_Results	= Cumulative summation for previous step	(2.3)
New_Cum_Results	= Cumulative summation for current step	(2.4)
Delta_Results	= Unmodified_Results - Modified_Results	(2.5)
New_Cum_Results	= Old_Cum_Results + Delta_Results	(2.6)

Activation of “Force Redistribution Module” is optional.

2.2.2.1.18 Store Pushover Data

This procedure is called at the end of each step of pushover increment to store observation node displacement, average displacement for user-defined floor and total base shear values. These data is used to construct pushover curves.

2.2.2.1.19 Check Member and Shell Stability

"Failure Simulation" procedure, which is also called sequential collapse analyses, is implemented in software CAVAS and application of this procedure is optional. This module is used to check the stability of members and shell elements at each step of the analyses and to remove the ones that fail. The details of "Failure Simulation" procedure are explained in Appendix A.

2.2.2.1.20 Activate Garbage Collector

This procedure is a part of "Failure Simulation" procedure and used to remove members which terminate the stability of the building. The details of "Failure Simulation" procedure are explained in Appendix A.

2.2.3 Post-Processor

The post-processor is composed of parsing and evaluation modules. The functions implemented in this module are used for:

- To parse outputs of SAP2000 at different stages during runtime.
- To evaluate input data (which are the outputs of *Central-processor* functions) and update stored data.
- To check stability at each step of analyses.

SAP2000 has its own structured output file with an extension of ".out". This file includes basically following parts, which are used with different modules of the developed software:

- Mass participation ratios.
- Displacement values for 6 mode shapes.
- Node displacements.
- Reaction forces.
- Member Forces.

When this module is called during runtime, required data is read by corresponding module according to the stage of analyses and stored in memory to be used with related functions as arguments.

There are 4 different Output parsing modules that have been implemented. Details of modules are as follows:

2.2.3.1 Dynamic Analysis Output Parsing Module

The argument of this module is dynamic analysis outputs, which are parsed to gather information about dynamic behavior of the building. The tasks conducted with this module are as flows:

1. To conduct dynamic analysis
2. To determine mass participation ratios

   The purpose to collecting information about mass participation ratios is to determine the X and Y dominant mode shapes. To determine dominant mode shapes all mass participation ratios are studied to get maximum values in each direction. The mode corresponding to the maximum value of mass participation ratios in X direction is "X Direction Dominant Mode" and similarly the mode corresponding to the maximum value of mass participation ratios in Y direction is "Y Direction Dominant Mode".

3. To determine natural mode shapes.

   The mode shapes are used in the pushover analyses as the push scheme. After the X any Y direction dominant modes are determined, the structure is forced to displace based on the node displacements of the selected mode shapes.

4. To parse and store displacements, reaction forces and member end forces to be used as dead load contribution.

2.2.3.2 Dead Load Analysis Output Parsing Module

The argument of this module is static analysis outputs which are parsed to gather information about dead load contribution. Before proceeding with each step in the pushover analysis, a separate dead load analysis is conducted. The purpose of doing this analysis is to redistribute dead loads for each displacement increment. The tasks conducted with this module are as flows:

1. To conduct static analysis.
2. To parse and store displacements, reaction forces and member end forces to be used as dead load contribution of modified structure.
3. To distribute forces and displacements along members.

In this section *Modified Structure* refers to; at each step of the pushover analyses the member axial load, moment, shear and torsion capacities are compared with the applied loads. During capacity design check members might be removed from the structure due to a failure (in this study the member removal process is activated in case of shear-torsion failure only) or plastic hinges can be formed at some locations. After removal of the members, new structure is called as "Modified Structure".

2.2.3.3 Pushover Analysis Output Parsing Module

The argument of this module is push analysis results which are conducted for each increment. Outputs are parsed to gather force and displacement data for the initial step. The data collected is used to update cumulative summation. The tasks conducted with this module are as flows:

1. To conduct push analysis for each increment.
2. To parse and store displacements, reaction forces and member end forces.
3. To distribute forces and displacements along members to update cumulative summation of forces and displacements.

2.2.3.4 Stability Check Output Parsing Module

The argument of this module is static analysis outputs which are parsed to check the stability of the structure. In pushover analyses, before proceeding with each step, the stability of the structure is checked. The tasks conducted with this module are as flows:

1. To conduct static analysis.
2. To parse output file to check stability of the structure.
   When the structure loses its stability, the output file does not contain any information regarding forces. This lack of information is indicative of stability loss and analysis stops immediately.

Since the software conducts pushover analyses for many different cases, overall analyses should not stop due to stability problem in any pushover scheme. If the stability of the structure is lost, it indicates that mechanism is formed. Pushover analyses must be finalized for the current case but analyses should go on with other ones. The continuation of the pushover analyses process is provided with this module.

2.2.3.5 Importance Evaluation Module

Areas under the pushover curves give an indication about the energy dissipated by the building during the pushover analyses. In Figure 2.5 the result of a performed pushover analyses for a structure is shown. In this figure "A_1" indicates the area under the curve which is at lower level (that is for modified structure). "A_2"indicates the area between two curves.

Energy dissipated by the original structure "ED_o", is defined as:

$$ED_o = A_1 + A_2 \quad (2.7)$$

Energy dissipated by the modified structure "ED_m", is defined as:

$$ED_m = A_1 \quad (2.8)$$

These values are computed and displayed automatically. *Member Importance Factor* computation procedure is described in following sections.

2.2.3.5.1 Importance Ratio

Importance ratio (member importance) concept is used to define ratio of drop in energy dissipation capacity of the original structure when a member is removed, to the energy dissipation capacity of the original structure.

Importance ratio "IR" is defined as:

$$IR = \frac{A_2}{A_1 + A_2} \tag{2.9}$$

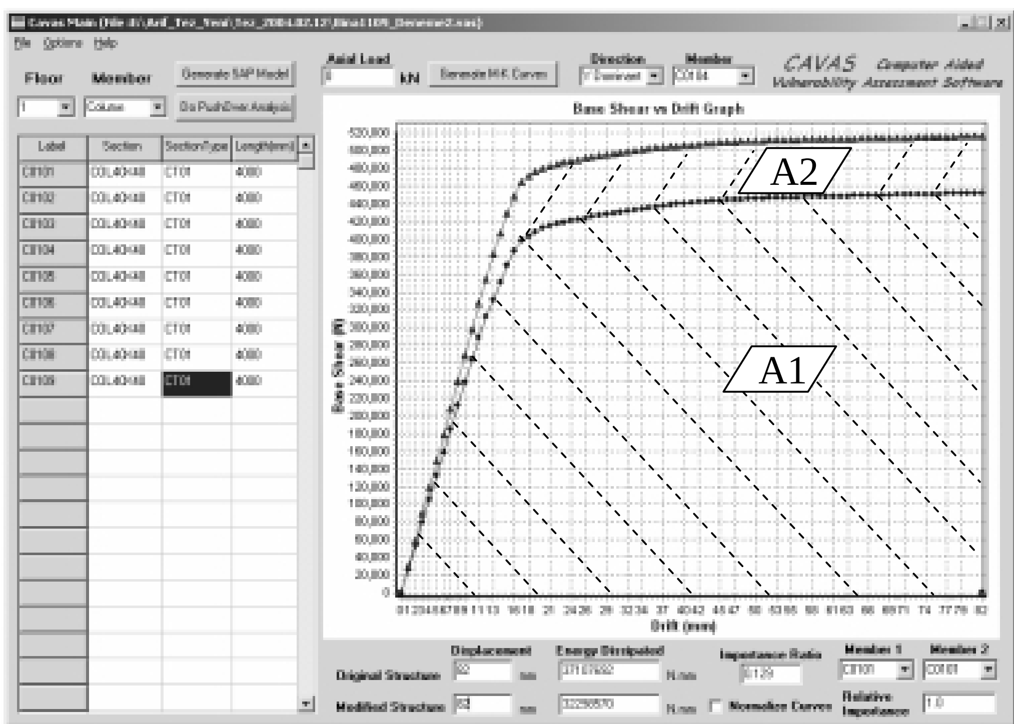

Figure 2.5 Example Pushover Analyses Results

2.2.3.5.2 Relative Importance

Relative importance is comparison of importance ratios of two members. Relative importance " IR_{ij} " is defined as:

$$IR_{ij} = \frac{IR_i}{IR_j}$$ Where IR_{ij} defines the relative importance of member "i" with respect to member "j". (2.10)

IR_{ij} : Importance ratio (member importance) of member "I"

IR_{ij} : Importance ratio (member importance) of member "j"

CHAPTER 3

CAPACITY CALCULATIONS

3.1 INTRODUCTION

In this chapter capacity calculation procedures implemented in CAVAS (which are "combined axial load & moment" and "combined shear & torsion" capacity calculation procedures), assumptions made and implemented section behaviors are described.

3.2 CAPACITY CALCULATIONS [13]

Implemented capacity calculation procedures are one of the basic topics in vulnerability index computation procedure proposed in this study. The procedures presented in this chapter control the failure mechanisms and redistribution of member forces. Capacity computation procedures and section properties should be defined properly in order to have correct pushover results. Generally, in assessment procedures the section properties of members are studied in detail in final stage, but in this study properties such as section dimensions, reinforcement percentage and distribution over section are necessary data to be provided. In some cases it might be hard to gather detailed information about the building. At such a situation, the solution is to provide section reinforcement distribution by guidance of current available standards. Minimum reinforcement requirements are proposed in Turkish Standards [13] for load carrying members. If reinforcement information is not available, vulnerability index computation can still be approximately performed by relying on the assumption that at least minimum reinforcement is provided.

Two major capacity relations are checked during pushover analyses. These are "combined axial load & moment" and "combined shear & torsion" capacity checks, which are generally the governing criteria that control the behavior of a building under seismic excitation.

Before presenting capacity calculation details and assumptions made, concrete and steel models used in section analyses are briefly explained.

3.2.1 Material Models

The capacities of members are utilized by simultaneous action of concrete and reinforcement. Therefore, individual properties of materials control the behavior of composite sections.

The material models that are implemented and used in this study are described in following sections.

3.2.1.1 Concrete Model

The main material used in reinforced concrete structures is the concrete.

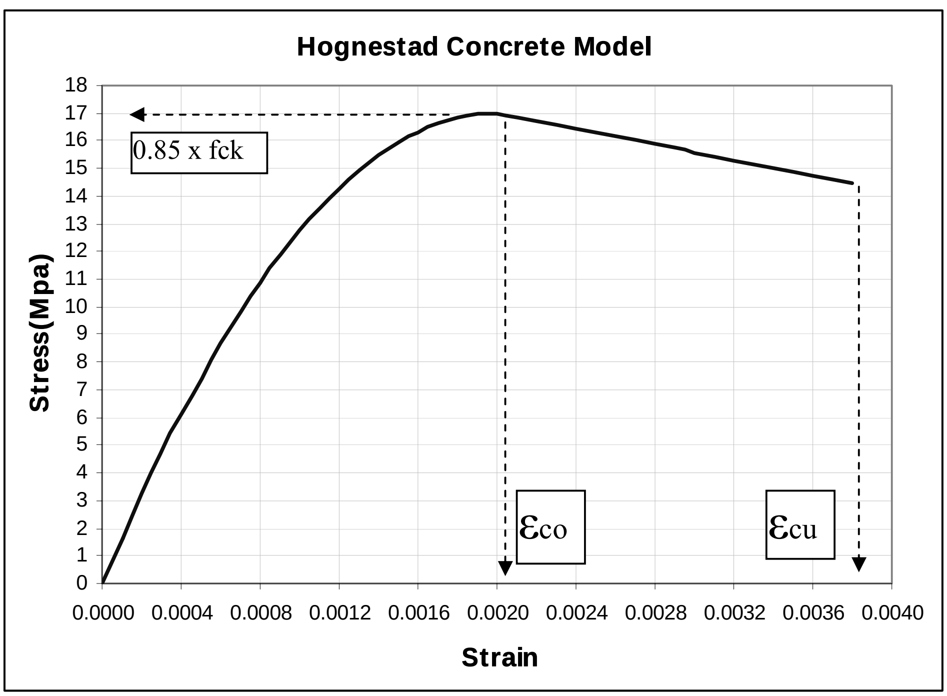

Figure 3.1 Hognestad Concrete Model

The main attribute of concrete that affects the capacity calculation is its strain-stress relation. There are some proposed concrete models, which define the variation of stress with respect to strain. One of the basic models is proposed by Hognestad. Indeed the Hognestad concrete model does present neither the behavior of confined nor unconfined concrete, but using this model for unconfined concrete is a practical approach. Figure 3.1 shows the model proposed by Hognestad.

In reinforced concrete structures, behavior of cast concrete when used with lateral reinforcement, in either form of continuous spirals or rectangular hoops, can not be considered without confinement effect. Ratio of confinement changes the strain-stress relation of concrete considerably. When concrete is exposed to high compression forces, the cover concrete crushes and core concrete under confinement tries to expand laterally due to Poisson's effect. This deformation is prevented by the lateral reinforcement, which applies lateral passive pressure on concrete. This is shown in Figure 3.2.

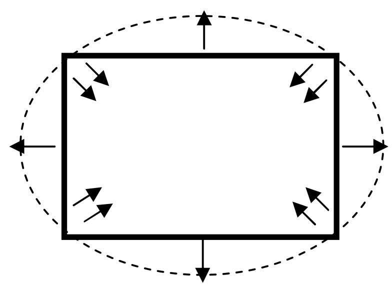

Figure 3.2 Poisson's Effect

There are number of proposed concrete models that take confinement effect into consideration. The model proposed by "Saatcioglu & Razvi" is implemented in this study. Figure 3.3 displays the model proposed by "Saatcioglu & Razvi". This model is applicable to rectangular sections reinforced with lateral reinforcement in form of rectangular hoops. The formulation of the proposed method is given with equations 3.1 to 3.14 and dimension variables of sections are displayed in Figure 3.4.

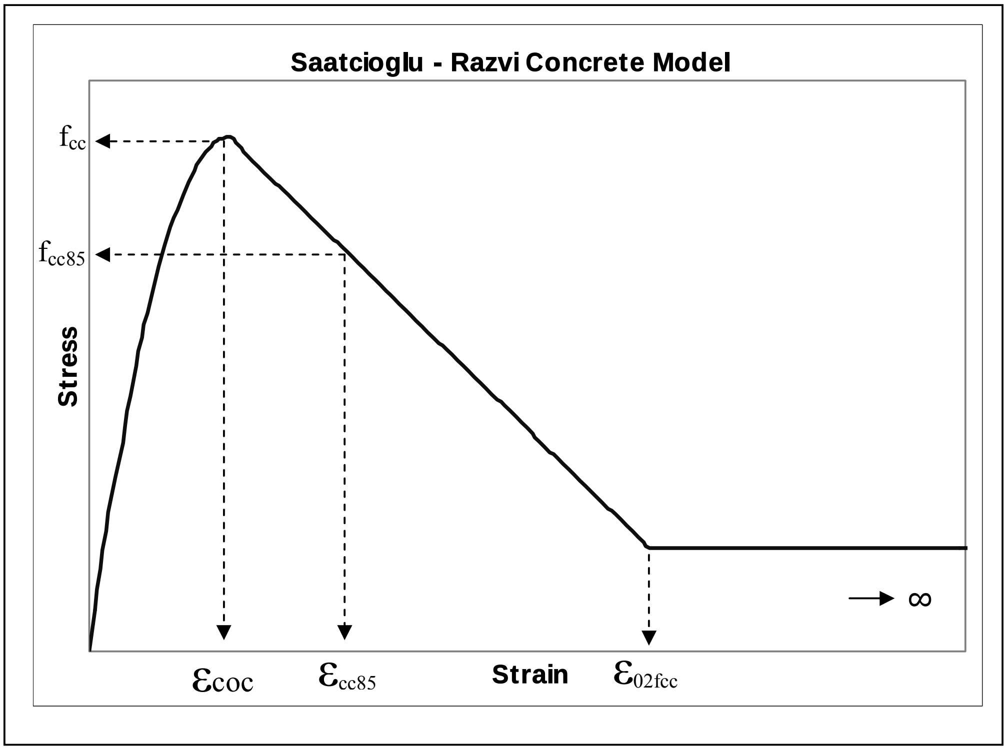

Figure 3.3 Saatcioglu – Razvi Concrete Model

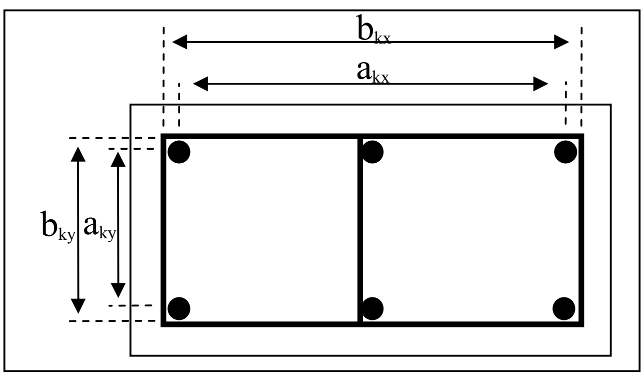

Figure 3.4 Cross-Section Dimension Variables

The formulation of the Saatcioglu – Razvi model is as follows:

$$\rho = \frac{\sum A_{ox} + \sum A_{oy}}{s \cdot (b_{kx} + by)} \tag{3.1}$$

$$\sigma_{2x} = \frac{\sum A_{ox} \cdot f_{ywk}}{s \cdot (b_{kx})} \tag{3.2}$$

$$\sigma_{2y} = \frac{\sum A_{oy} \cdot f_{ywk}}{s \cdot (b_{ky})} \tag{3.3}$$

$$\beta_x = 0.26 \cdot \sqrt{\left(\frac{b_{kx}}{a_x}\right) \cdot \left(\frac{b_{kx}}{s}\right) \cdot \left(\frac{1.0}{\sigma_{2x}}\right)} \leq 1.0 \tag{3.4}$$

$$\beta_y = 0.26 \cdot \sqrt{\left(\frac{b_{ky}}{a_y}\right) \cdot \left(\frac{b_{ky}}{s}\right) \cdot \left(\frac{1.0}{\sigma_{2y}}\right)} \leq 1.0 \tag{3.5}$$

$$\sigma_{2ex} = \beta_x \cdot \sigma_{2x} \tag{3.6}$$

$$\sigma_{2ex} = \beta_y \cdot \sigma_{2y} \tag{3.7}$$

$$\sigma_{2e} = \frac{(\sigma_{2ex} \cdot b_{kx}) + (\sigma_{2ey} \cdot b_{ky})}{(b_{kx} + b_{ky})} \tag{3.8}$$

$$k_3 = 0.85 \tag{3.9}$$

$$k_1 = \frac{0.67}{\left(\frac{\sigma_{2e}}{k_3 \cdot f_{ck}}\right)^2} \tag{3.10}$$

$$f_{cc} = k_3 \cdot fck + k_1 \cdot \sigma_{2e} \tag{3.11}$$

$$\lambda = \frac{k_1 \cdot \sigma_{2e}}{k_3 \cdot fck} \tag{3.12}$$

$$\varepsilon_{coc} = \varepsilon_{co} \cdot (1 + 5 \cdot \lambda) \tag{3.13}$$

$$\varepsilon_{cc85} = 260 \cdot \rho \cdot \varepsilon_{coc} + \varepsilon_{cu} \tag{3.14}$$

- In this study, ***tension capacity*** of concrete is ignored.

3.2.1.2 Steel Model

Since concrete is weak in tension, longitudinal steel bars are used with concrete to take care of tension. The importance and contribution of using lateral reinforcement have been discussed in section 3.2.1.1. For reinforced concrete sections, one of the basic assumptions is the concept of perfect bond between concrete and steel bars. Based on this assumption and studies conducted for steel models, tri-linear steel model is implemented in this study.

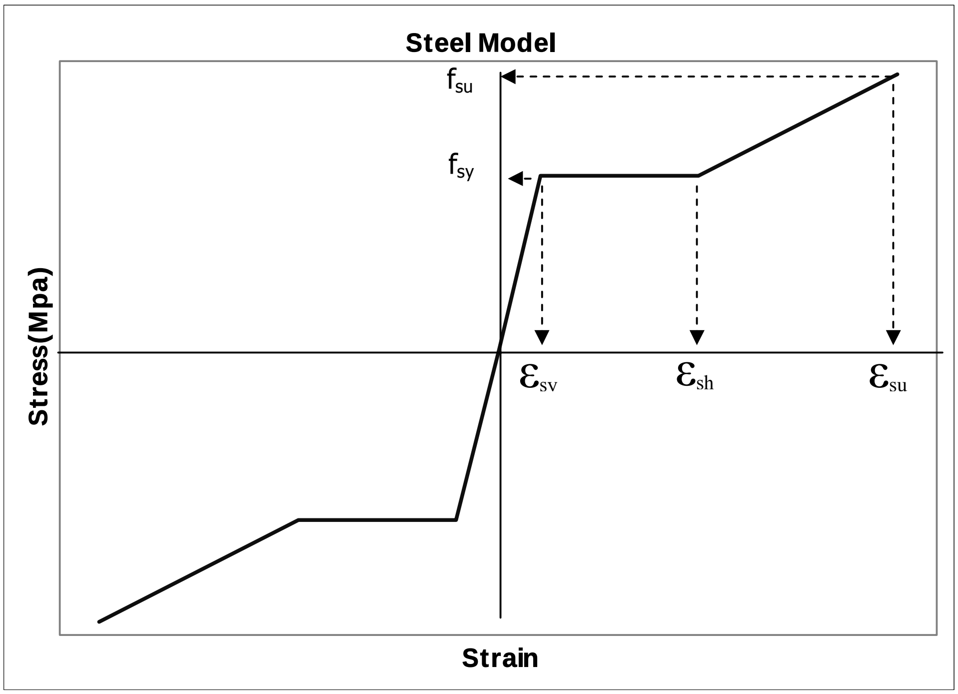

Figure 3.5 Tri-linear Steel Model

Model variables are defined in the software with default values of:

- $\varepsilon_{sy} = f_{sy} / E_s$ where "f_{sy}" is yield strength of steel, that is basic input, and "E_s" is modulus of elasticity, that is basic input.
- $\varepsilon_{sh} = \varepsilon_{su}$
- $\varepsilon_{su} = 0.1$ ε_{su} and "f_{su}" values can be modified.

As above mentioned details indicate, default steel model implemented has elasto-plastic behavior which can be modified by changing the model variables.

3.2.2 Capacity Calculations

Every member (object in C++) has a member variable called "ColType" object, which holds all the information regarding the member section. As soon as the section properties are gathered, capacity calculations are conducted in this object for the corresponding member. This process is carried out in "Pre-processor Module". Since the capacity calculations are finalized before "Central- processor" is called, the efficiency of the software increases considerably, because during analyses, the time is not lost due the capacity calculation procedures.

Capacity calculations are processed in 3 stages as follows:

1. Section dimensions and reinforcement data is read.
2. Related computations are carried out.
3. Results are stored in related objects.

3.2.2.1 Input Reading

In this module the section properties for each section type are read. The parsed information is:

- Member type label.
- Member type name.
- Height of section.
- Width of section.
- Concrete material type label.
- Reinforcement material type label.
- Three columns are for tie bar data.
- Rest is for longitudinal bar data.

Example section property data line is as follows:

```
" CT01 COL30X30  400.0  300.0  CONC BAR  2 2 12 3*2 16 "
```

3.2.2.2 Capacity Calculation Procedures

Capacity calculations are carried out for the structural members; columns, beams and shear walls only. Floors are assumed to be capable to carry the applied forces through the end of the analyses. Column and beams have same capacity calculation procedures. Due to geometric properties, different capacity computation procedures are implemented for shear walls.

Based on above-mentioned explanations, in this section the capacity calculations are studied for:

- Beams & Columns
- Shear Walls

separetally.

Note: During explanations of capacity calculations the terminology used to define axis is as follows:

- Presentation "$_{33}$" indicates strong axis
- Presentation "$_{22}$" indicates weak axis

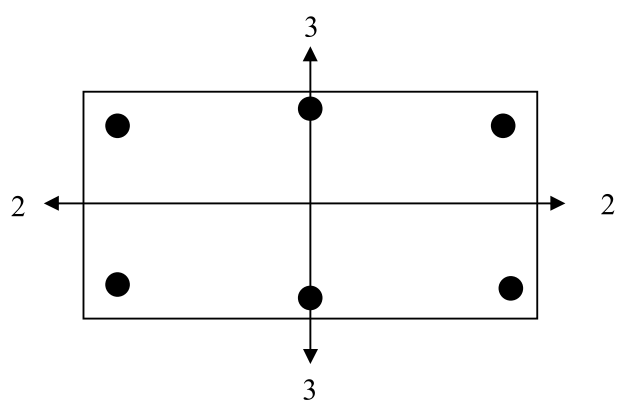

Figure 3.6 Section Axes Designation

3.2.2.2.1 Capacity Calculations for Columns & Beams

As far as the behavior of the framed type structures, which are composed of beams and columns, are considered, the majority of the lateral resistance is provided by columns under seismic excitations. Beams are generally responsible for the ductility. During excitations, columns are exposed to shear forces, torque, moments and axial forces and beams are exposed to shear forces, torsion and moments.

The capacity calculation procedures implemented in CAVAS are as follows:

3.2.2.2.1.1 Shear Capacity Computations for Beams & Columns [13]

$$V_r = V_w + V_c \quad [13] \qquad (3.15)$$

Shear capacity in 2-2 direction:

$$V_{r22} = (\frac{A_{sw22}}{s}) \cdot f_{ywk} \cdot d_{22} + \alpha \cdot f_{ct} \cdot b_{w22} \cdot d_{22} \quad [13] \qquad (3.16)$$

Shear capacity in 3-3 direction:

$$V_{r33} = (\frac{A_{sw33}}{s}) \cdot f_{ywk} \cdot d_{33} + \alpha \cdot f_{ct} \cdot b_{w33} \cdot d_{33} \quad [13] \qquad (3.17)$$

α is the coefficient that controls the contribution of concrete during shear capacity computations. In TS500 [13] it is indicated that: In cases where the concrete strength is not tested, concrete contribution should be ignored.

In TS500 concrete contribution to the shear capacity of the section is defined as:

$$V_c = 0.8 \cdot V_{cr} = 0.5 \cdot f_{ct} \cdot b_w \cdot d \quad [13] \qquad (3.18)$$

3.2.2.2.1.2 Torsion Capacity Computations for Beams & Columns [13]

Torsion capacity: $T_c = (\frac{A_{to}}{s}) \cdot 2 \cdot A_e \cdot f_{ywk}$ [13] (3.19)

3.2.2.2.1.3 Axial Load & Moment Capacity Computations for Beams& Columns

Axial load and moment capacities of a section are not independent from each other. The relation between them can only be simulated by interaction curves. There is a module implemented in the software, which computes interaction curve data. This module computes the moment capacities of the section for axial forces that vary between tension and compression capacities of the section.

Since the axial loads applied on the beams are generally small, the moment capacity of the beams can be computed with simplified methods as follows:

$$M_r = \mathrm{A_s} \cdot \mathrm{f_{yk}} \cdot (j) \cdot d \quad \text{Where } j \cong 0.85 \qquad (3.20)$$

where A_s : Area of bottom longitudinal reinforcement.

f_{yk} : Yield strength of steel.

d : Depth of the section

For columns, the situation is completely different. Axial forces applied to members change through out the analyses. To be able to simulate this change and take axial load changes in into consideration, capacity checks are conducted based on interaction curve relations.

In order to achieve the objectives of this study, the plastic behavior of the structure should be simulated properly. Plastic behavior of structure can be simulated by taking plastic behavior of members into consideration. Therefore instead of using section moment capacities, moment values that cause yielding of section is taken into account in capacity comparisons. Therefore the interaction curve results refer to the relation of axial load with yielding moment capacity.

As mentioned above, for different axial load levels, yielding moment calculations are carried out. For this purpose, "Moment-Curvature" computation procedure is implemented in the software.

The procedure is as flows:

1. A "ε_t" (top concrete compression strain) value is assumed. This value is increased from 0.0001 to "$\varepsilon_{02\text{fcc}}$" with increments of 0.0001.
2. A " c " (detph of the neutral axis from top) value is assumed.
3. The concrete in compression above the assumed "c" value is divided into slices. The thickness of the silices are defined before starting the procedure and this effects the accuracy and time required to finish computations. The default value is 1mm which gives successful results.
4. The midpoint strains of the concrete slices are determined.(The midpoint strains of the concrete slices is assumed to be representative for whole slice)
5. Steel strains are calculated.
6. With the calculated strains the stresses and forces at each slice and reinforcement bars are calculated. This calculation is based on the models implemented.
    - For cover concrete, Hognestad concrete model is applied.
    - For confined concrete, Saatcioglu-Razvi concrete model is applied.
    - For steel, user-defined steel model is applied.
7. The resultant reaction is calculated (Reaction forces generated in concrete under compression and steel under tension and compression.)
8. If the difference between calculated reaction and the applied load is in between the tolerance defined (the default tolerance is 100 N), the moment corresponding to assumed " c " value is calculated. Otherwise " c " is increased until force equilibrium is satisfied.
9. The moment corresponding to the " c " is calculated by taking moments of all slice forces and bar forces with respect to geometric center.
10. At the end of analysis for each strain increment the curvature values are stored. Curvature is calculated with relation $K = \varepsilon_t / c$.

For the section defined in Figure 3.7, "Moment-Curvature" relations for two different axial load levels of 0 kN and 100 kN are displayed in Figures 3.8 and 3.9, respectively.

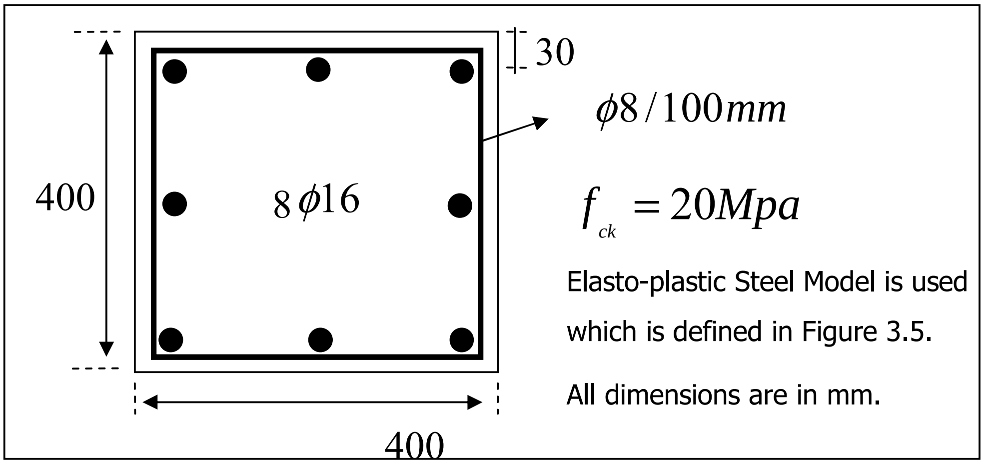

Figure 3.7 Example Cross-Section with Reinforcement Details

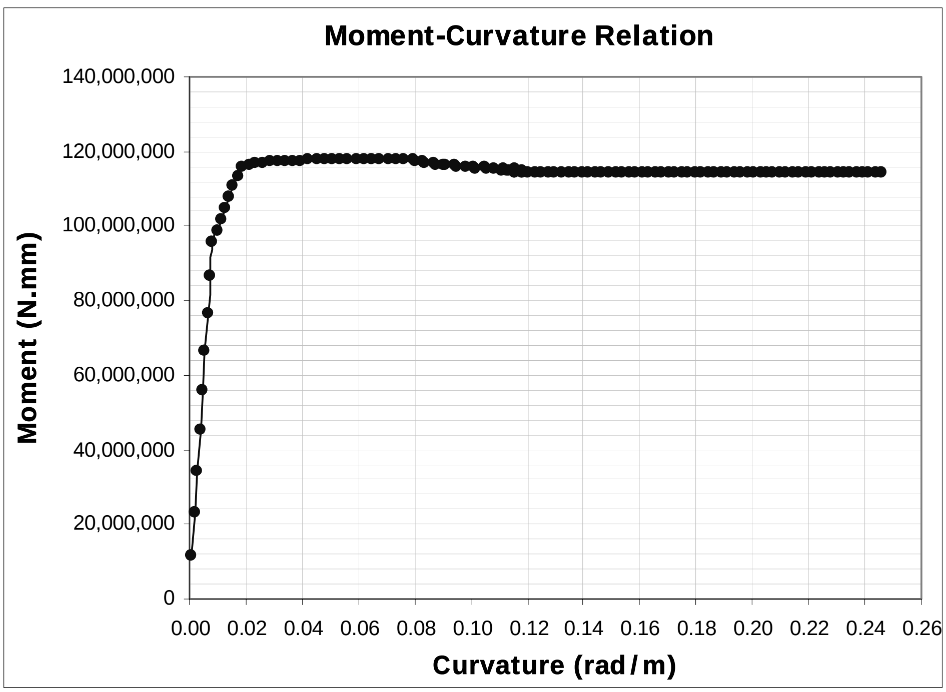

Figure 3.8 Moment Curvature Relation for Axial Load = 0 kN

When relations given in Figures 3.9 and 3.10 are studied, it is observed that yielding moment values are lower than moment capacity corresponding to crush of cover concrete. This fact gains importance as the applied axial loads get higher. As the relations present, the real behavior of members can be simulated by allowing the member to survive until cracking moment capacity is reached and then unloading to the yielding moment capacity. In CAVAS such a behavior is not implemented yet. However the section behaviors are simulated as if the section

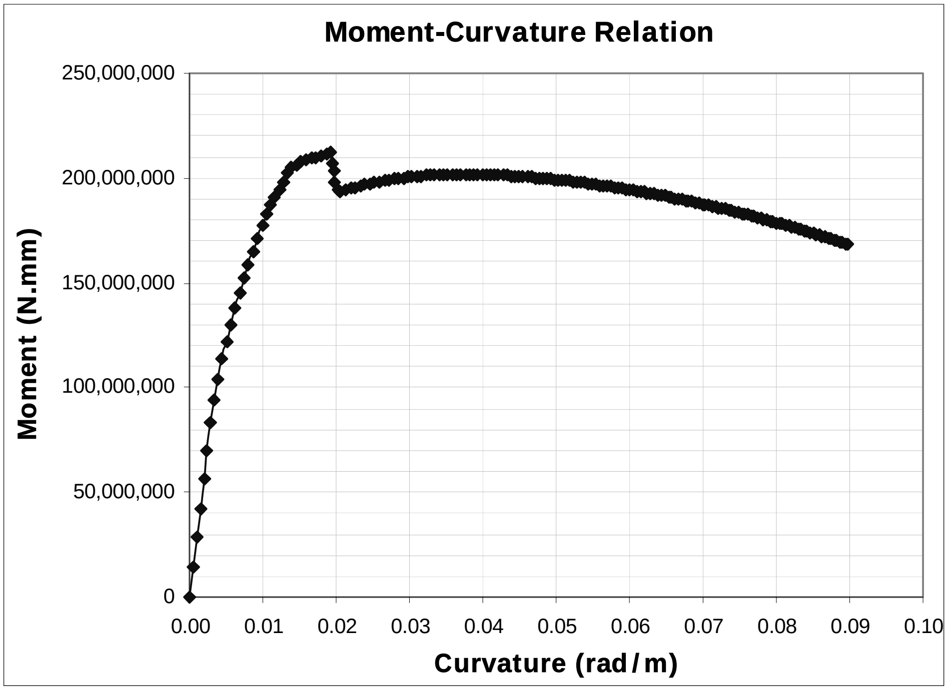

Figure 3.9 Moment Curvature Relation for Axial Load = 1000 kN (Compression)

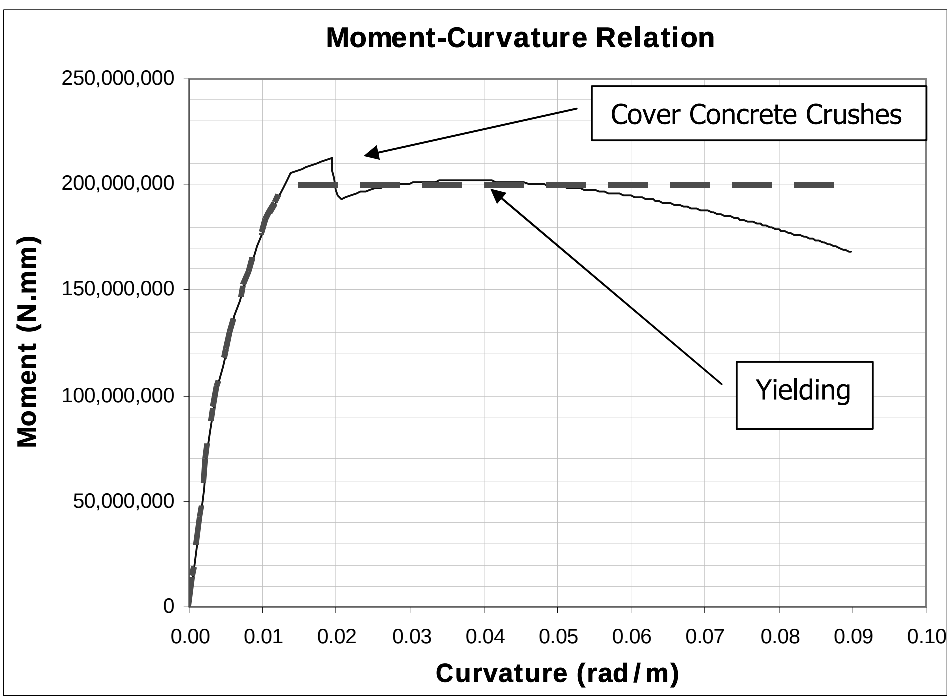

Figure 3.10 Modified Moment Curvature Relation

keeps its yielding moment capacity after yielding moment value is reached. This behavior is shown in Figure 3.10.

During the analyses, at capacity comparison stage, yielding moments corresponding to axial load level is called with associated function. If the yielding of member ends takes place, member keeps that yielding moment through out the analyses even if the axial load applied on the member changes. The procedure for the computation of interaction curve data is as follows:

1. Axial load is increased from level of tension capacity of section to the compression capacity.
2. Yielding moment capacity is determined by taking the average of about 30 data point after cover concrete crushes.

During interaction relation computations, the average of the yielding part of Moment-Curvature data for the corresponding axial load is taken as yielding moment. This approach introduces some discrepancy between the yielding moment values and moment values corresponding to crush of cover concrete as the axial load on the member gets higher. This is illustrated in Figure 3.11, which shows the interaction relation for the section defined in Figure 3.7.

The small error introduced due to this discrepancy is neglected during the analyses. This is most appropriate approach, since unloading scheme is quite complicated and planned as a future study. For high axial load levels, the error has no affect on the behavior as far as the design obligations are considered. Because, in design standards designing members for such high axial loads is not allowed. Even if the members are exposed to high compression forces, the error introduced is relatively small as shown in Figure 3.11.

The main attribute that controls the discrepancy between above-mentioned two approaches (yielding moment and moment corresponding to cover concrete crushing) is cover concrete thickness. For section defined in Figure 3.7, interaction relation computations are repeated for cover concrete thickness of 20mm instead of 30mm. The revised interaction curves are obtained as displayed in Figure 3.12.

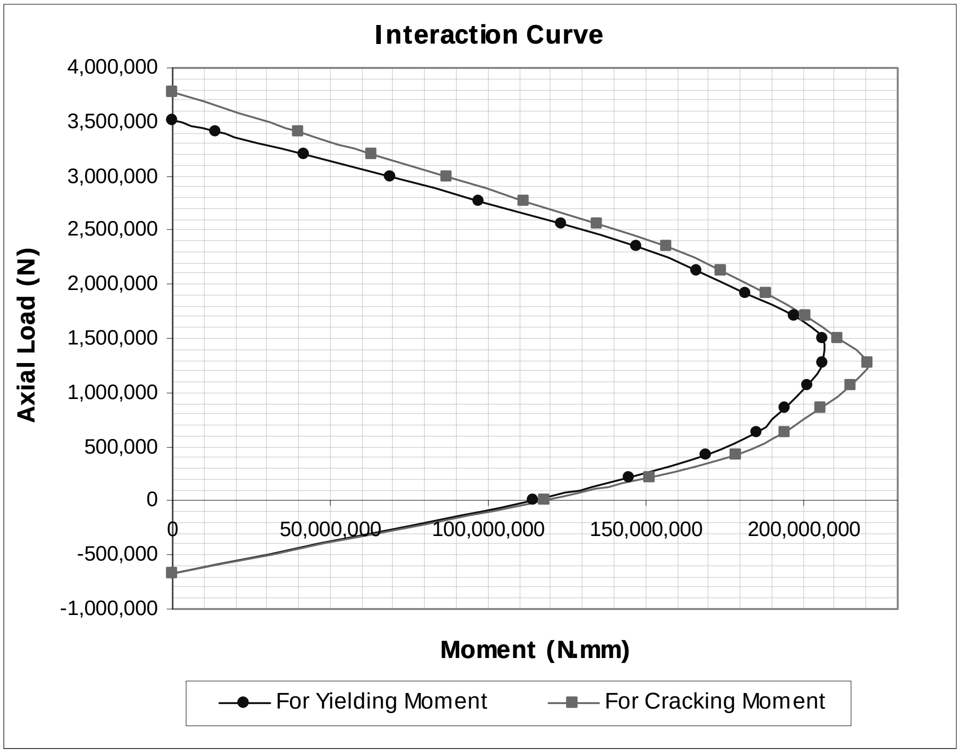

Figure 3.11 Interaction Relation for Cover Concrete Thickness = 30mm

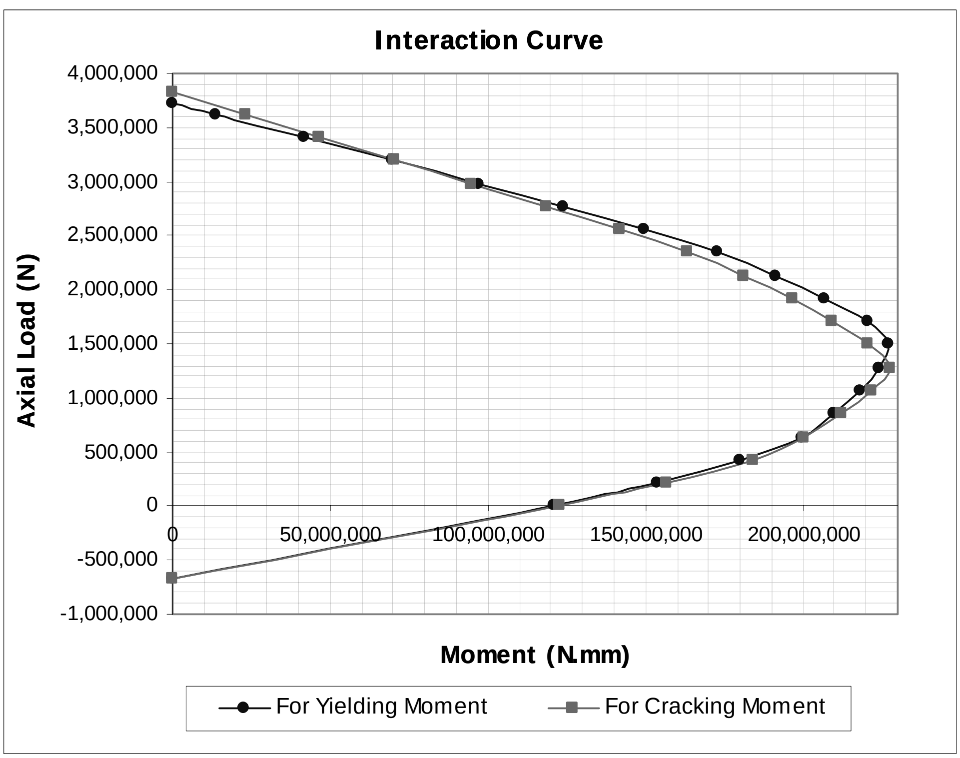

Figure 3.12 Interaction Relation for Cover Concrete Thickness = 20mm

3.2.2.2.2 Capacity Calculations for Shear Walls

Shear Walls are one of the most important members as far as the seismic performance of a structures is considered. The appropriate placement of these members within floor plans increases the lateral load capacity of the building considerably. Besides, wrong placement can yield destructive shear force distribution due to generated torsion during seismic excitation.

Shear walls are designed to resist major percentage of lateral forces applied on the structure during seismic excitations and to avoid the generation of shear/bending failures of columns. Shear failure is a brittle failure type and should be avoided.

3.2.2.2.2.1 Shear Capacity Calculation for Shear Walls [13,7]

Shear capacity in 2-2 direction:

$$V_{r22} = \sum A_{ch} \cdot \left(0.65 \cdot f_{ct} + \rho_n \cdot f_y\right) \quad [7] \quad (3.21)$$

Shear capacity in 3-3 direction:

$$V_{r33} = V_w + V_c \quad [13] \quad (3.22)$$

$$V_{r33} = \left(\frac{A_{sw33}}{s}\right) \cdot f_{ywk} \cdot d_{33} + \alpha \cdot f_{ct} \cdot b_{w33} \cdot d_{33} \quad [13] \quad (3.23)$$

α is the coefficient that controls the contribution of concrete during shear capacity computations. In TS500 [13] it is indicated that: In cases where the concrete strength is not tested, concrete contribution should be ignored.

In TS500 [13] concrete contribution to shear capacity of the section is defined as:

$$V_c = 0.8 \cdot V_{cr} = 0.5 \cdot f_{ct} \cdot b_w \cdot d \quad [13] \quad (3.24)$$

3.2.2.2.2.2 Torsion Capacity Computations for Shear Walls [13]

Torsion capacity: $$T_c = (\frac{\mathrm{A_{to}}}{\mathrm{s}}) \cdot 2 \cdot \mathrm{A_e} \cdot \mathrm{f_{ywk}}$$ [13] (3.25)

3.2.2.2.2.3 Axial Load – Moment Capacity Computations for Shear Walls

The computation procedure is same as for Columns and Beams described in section 3.2.2.2.1.3.

3.2.3 Implemented Section Behaviors

Pushover analyses require member capacities to be checked with the applied loads for all members at each step. During capacity check process, if the section capacity of any member is exceeded, related modifications are applied. The modifications and their application conditions are described below for

- Beams and Columns
- Shear Walls

separately.

3.2.3.1 Behavior of Columns & Beams Subjected to Shear & Torsion [11,13]

Both applied shear and torsion generates shear stresses on the members. Therefore combined shear stresses must be checked with combined shear and torsion capacity. The interaction theory derived by Ersoy [11] and Ferguson for estimating the diagonal cracking strength can be used to predict ultimate strength of members with web reinforcement. The derived relation is:

$$\left(\frac{T_d}{T_{ro}}\right)^2 + \left(\frac{V_d}{V_{ro}}\right)^2 = 1.0$$ [11] (3.26)

where

T_d : Applied torque

V_d : Applied shear

V_{ro}: Ultimate shear capacity for applied Torque = 0;

$$V_{ro} = V_w + V_c = (\frac{A_{sw}}{s}) \cdot f_{ywk} \cdot d + \alpha \cdot f_{ct} \cdot b_w \cdot d \quad [13] \qquad (3.27)$$

T_{ro}: = Ultimate torsion capacity for applied V = 0;

$$T_{ro} = (\frac{A_{to}}{s}) \cdot 2 \cdot A_e \cdot f_{ywk} \quad [13] \qquad (3.28)$$

The Figure 3.13 displays the relation defined with formula 3.25.

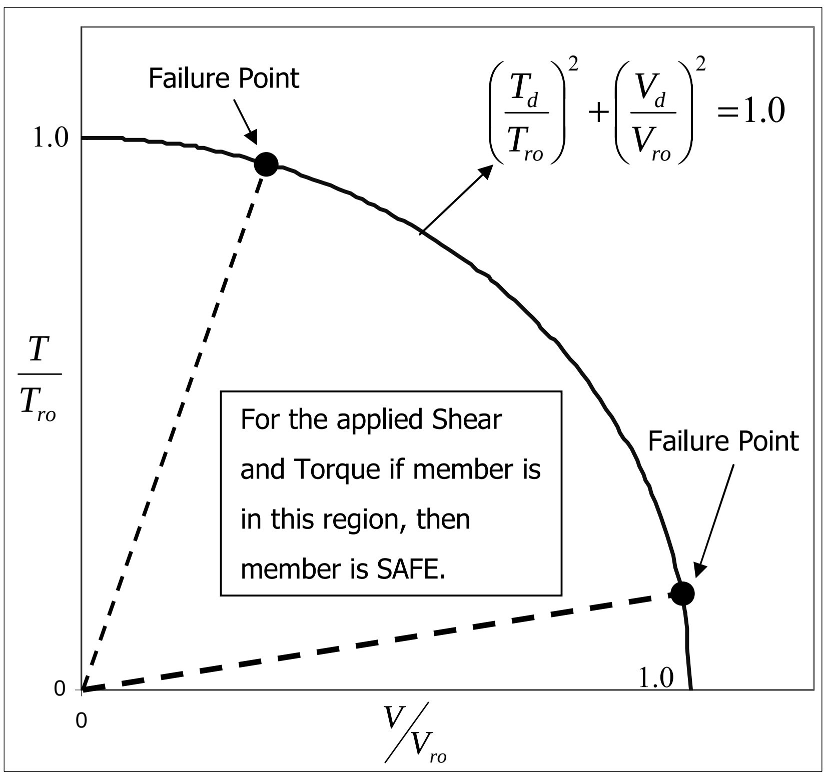

Figure 3.13 Behavior of Section under Torsion and Shear

Since the shear failure is brittle, the members subjected to shear and torsion that is exceeding combined capacity, are erased form the model and removed form the analysis. This modification is also a punishment for the building, which has members fail in shear during the analyses.

In Figure 3.13, dashed lines show the behavior of a section that fails under shear and torsion with two different loading schemes. As soon as combined capacity is exceeded, member fails and releases its entire load, meaning it has no shear resistance any more.

The combined shear and torsion check is conducted in two directions separately. It is assumed that shear failures in both directions are independent from each other.

3.2.3.2 Behavior of Columns & Beams Subjected to Axial Load & Moment [11]

Beams and columns are generally subjected to biaxial moments under seismic excitations. In order to check axial load & moment capacity of a member, interaction surface must be generated and studied. This surface is generated by planes of biaxial moment capacity for different levels of applied axial loads. Since generation of 3D surface is not practical, this surface is approximated by using estimated relations, which are derived to simulate biaxial bending.

Bresler proposes one of the approximations used for the relation with the following formulation:

$$\left(\frac{M_{zx}}{M_{zxo}}\right)^{\alpha 1} + \left(\frac{M_{zy}}{M_{zyo}}\right)^{\alpha 2} \leq 1.0 \quad [11]\ (3.29)$$

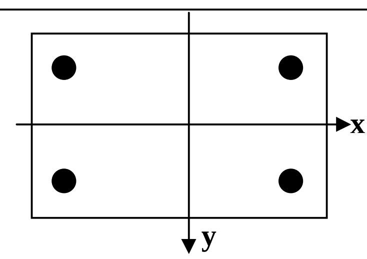

Figure 3.14 Axes Designation

Where M_{zx} : Applied moment about x-axis.

M_{zy} : Applied moment about y-axis.

M_{zxo} : Uniaxial flexural strength about x-axis under applied axial load.

M_{zyo} : Uniaxial flexural strength about y-axis under applied axial load.

The constants α1 and α2 depend on column properties and they are determined experimentally. In this study British code proposal is implemented as an option. In British code α1 and α2 depend on applied axial load level. For low axial loads they have value of 1.0 and for high axial loads the values go up 2.0. In between, the values show linear increase. The variation of α1 and α2 with respect to axial load level are as follows:

If $\left(\dfrac{N}{N_o}\right) < 2.0$ α1 and α2 = 1.0 (3.30)

If $0.2 \leq \left(\dfrac{N}{N_o}\right) \leq 8.0$ α1 and α2 = $0.67 + 1.67 \cdot \left(\dfrac{N}{N_o}\right)$ (3.31)

If $\left(\dfrac{N}{N_o}\right) > 8.0$ α1 and α2 = 2.0 (3.32)

Where

N : Applied axial load.

N_o : Ultimate load capacity for applied Mzx = 0 and Mzy = 0.

Other simplified approach, which is implemented in the software as an option, is defined as follows:

$$\left(\frac{M_{zx}}{M_{zxo}}\right)^2 + \left(\frac{M_{zy}}{M_{zyo}}\right)^2 \leq 1.0 \qquad (3.33)$$

This simplified approach is proposed by the author as an alternative method to Bresler's formulation. The proposed relation is same with the Bresler's formulation with the condition that "N/N_o" ratio is always greater than "0.8". The pushover analyses results showed that the application of proposed method by the author does gives successful results as far as the overall structural behavior is considered.

During each step of analyses, above-mentioned capacity checks are conducted. If the member yields under applied loads, it keeps the yielding moment through the end of the analyses. This behavior is simulated with the placement of hinges to corresponding nodes. In this study, member failure under axial load and moment is not implemented. To realize this failure mode, displacement should also be controlled by curvature check.

In order to simulate flexural behavior it is assumed that formation of plastic hinges take place simultaneously in both directions. With this implementation more realistic structural behaviour is provided. The implementation of this procedure does also show the flexibility of the software. This assumption is based on a fact that if plastic hinging take place in one of the principle directions, it is not possible to keep initial moment capacity in other principle direction. Because, theoretically formation of plastic hinges causes changes in the section properties.

The summary for the implemented behavior of the section under axial load & moment is demonstrated in Figure 3.15. In Figure 3.15, dashed lines show the behavior of a section that is plasticized under two different loading schemes. As soon as the plastic hinges formed, member keeps the moments that cause yielding through out the analyses in both directions.

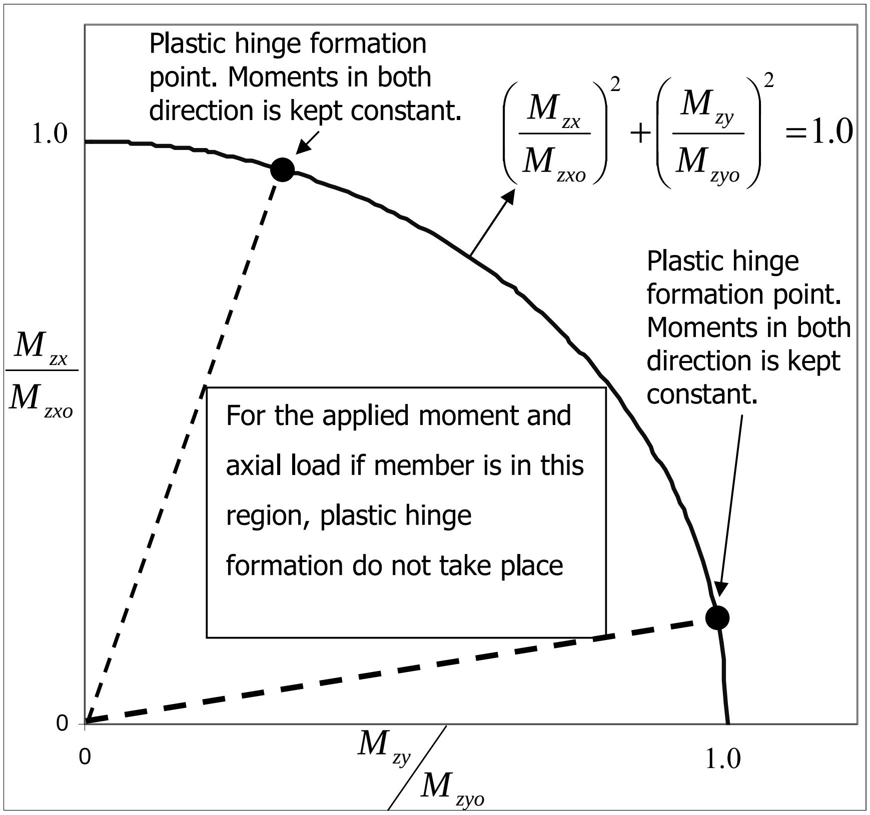

Figure 3.15 Behavior of Section under Axial load and Moment

3.2.3.3 Behavior of Shear Walls Subjected to Shear & Torsion [12,13,7]

The implemented shear wall behavior under shear stresses is similar with columns. As indicated earlier, for shear walls shear capacity computation in 2-2 direction is different from columns. The interaction theory derived by Ersoy and Ferguson for estimating the diagonal cracking strength is applied to define shear wall behavior.

$$\left(\frac{T_d}{T_{ro}}\right)^2+\left(\frac{V_d}{V_{ro}}\right)^2=1.0 \qquad [12] \qquad (3.34)$$

Where

T_d : Applied torque

V_d : Applied shear

V_{ro}: Ultimate shear capacity for applied Torque = 0;

$$V_{ro} = \sum A_{ch} \cdot \left(0.65 \cdot f_{ct} + \rho_n \cdot f_y\right) \quad \text{(in 2-2 direction) [7]} \quad (3.35)$$

$$V_{ro} = (\frac{\mathrm{A_{sw33}}}{\mathrm{s}}) \cdot \mathrm{f_{ywk}} \cdot \mathrm{d_{33}} + \alpha \cdot \mathrm{f_{ct}} \cdot \mathrm{b_{w33}} \cdot \mathrm{d_{33}} \quad \text{(in 3-3 direction) [13]} \quad (3.36)$$

T_{ro}: = Ultimate torsion capacity for applied V = 0;

$$T_{ro} = (\frac{\mathrm{A_{to}}}{\mathrm{s}}) \cdot 2 \cdot \mathrm{A_e} \cdot \mathrm{f_{ywk}} \quad [13] \quad (3.37)$$

The combined shear and torsion check is conducted in two directions separately.

3.2.3.4 Behavior Of Shear Walls Subjected to Axial Load & Moment

Shear walls are also subjected to biaxial moments under seismic excitations as beams and columns. But due to geometric properties of shear walls, implemented behavior under axial load and moment is slightly different than behavior implemented for columns and beams. Combined axial load & moment check is conducted uni-axially in both directions. Simply it is assumed that applied moments in both directions is independent from each other. In order to perform axial load & moment capacity check, it is required to gather interaction curve data. This is performed with the same procedures applied for columns and beams.

The relation proposed is as follows:

$$\left(\frac{M_{zx}}{M_{zxo}}\right) \leq 1.0 \quad \text{and} \quad \left(\frac{M_{zy}}{M_{zyo}}\right) \leq 1.0 \quad (3.38)$$

M_{zx} : Applied moment about x-axis (weak axis).

M_{zxo} : Uniaxial flexural strength about x-axis under applied axial load.

M_{zy} : Applied moment about y-axis (weak axis).

M_{zyo} : Uniaxial flexural strength about y-axis under applied axial load.

At each step of the pushover analyses above mentioned capacity checks are conducted. If the shear wall yields under applied loads, it keeps the yielding moment through the end of the analyses. This behavior is simulated with the placement of hinges to corresponding nodes. Here, it is assumed that a member does not fail under axial load & moment. To realize total failure, displacement should also be controlled by a curvature check. This check is not implemented yet.

CHAPTER 4

PROGRAMMING ISSUES

4.1 INTRODUCTION

This chapter is devoted to programming issues. After a small discussion on Object Oriented code design and C++, information about the program flow and the implemented classes will be explained in details. The interface of the software is introduced in this chapter.

4.2 OBJECT ORIENTED CODE DESIGN [13]

In daily life, everything is an object and that is why we can identify them easily. Indeed, identifying objects is some kind of thinking style. Physically, we can distinguish objects from each other; either with their properties or with the actions they perform. C++ is “Object Oriented Language”, which gives programmer flexibility to implement codes with the rules of daily life. It may seem illogical to match life with programming, but the basis of C++ programming language is composed of objects, which are also basis of the environment that we are living in.

In code design and implementation, as the domain of the program gets complex, controlling variables becomes harder and harder. Finite element method codes are good example of complex codes, which contain variety of information about the members, joints, restraints etc. Programs, which evaluate outputs of FE analyses, should have capability to manipulate the data in a modular manner. Designing stage of such programs is generally harder than writing the code itself. In designing stage, below mentioned attributes of the program are studied and planned:

- Ability to permit modifications on the program modules and relations between each other.
- Ability to permit change of code.
- Understandability of the code.

Above-mentioned properties of C++ provide flexibility to the programmer in coding stage and to handle complex problems

One of the basic concepts in C++ is “class”. Object is an instance of a class. As an example, car is a class whereas different models are the objects. An object contains its own properties (e.g., color, width, number of seats etc.) and actions it can take (e.g., ability to speed up, break etc.). Presence of class and data encapsulation notion in C++, control over the data access processes serve robustness in coding.

In object oriented programming, the classes with their member variables and member functions construct structured codes. In a well-defined code, changing attributes of classes does not necessitate modifications in other parts of the code. This property enables addition of new modules, which serves for the usability of the code in future. This property is frequently used in coding of CAVAS.

With one of the very important property of C++, unlike classical programming approach, it is not a necessity to define array sizes during programming stage, which prevents the allocation of memory unnecessarily. With dynamic memory allocation facility, the array dimensions are defined during runtime and the arrays are created accordingly. This provides proper use of computer memory through out the analysis. Besides, creating arrays dynamically gives possibility to free memory during runtime, which prevents RAM of the computer to be allocated with unnecessary data. This property has very high importance in CAVAS, because bulk of data must be stored for each analyses step and release of memory is inevitable issue. More detailed information about object oriented code design can be found in book titled “Problem Solving with C++” [15].

4.3 PROGRAM ARCHITECTURE AND CAPABILITIES

After giving brief information about object oriented programming basics, details of software Cavas will be explained under two main titles, which are:

1. Implemented Classes.
2. Graphical User Interface Options.

4.3.1 Implemented Classes

In coding, using built-in classes simplifies work to be done considerably. Besides predefined classes, many classes are implemented specifically for the software Cavas to serve for the requirements of pushover analyses and data storage.

In Cavas, following discrete classes are designed in order to carry out the bulk of complex mathematical operations, avoiding code clouding with loops and indexes, which is more susceptible to errors.

- Grid Class
- MatType Class
- SectionProps Class
- Coltype Class
- Column Class
- ShearWall Class
- Beam Class
- Node Class
- Shell Class
- Parcel Class
- Floor Class
- Displacement Database Class
- Force Database Class
- Bina Class

4.3.1.1 Grid Class

Grid class stores the label of the grid and the variables that defines the grid object. The aim of implementing this class is to store the fundamental information to be used during construction of node, column, beam and shear wall objects.

Member functions implemented in Grid class are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables.
- Default Destructor.
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.

4.3.1.2 MatType Class

MatType class stores the label of the material type to be used in the analyses and the variables that defines the material properties as mass, modulus of elasticity, poisons ratio etc. The aim of implementing this class is to store the fundamental information to be used during constructing of ColType objects.

Member functions implemented in MatType class are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables.
- Default Destructor.
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Additional functions: "PrepareSapMatOutput" function is used for preparation of "MATERIAL" data block for Sap2000 input file.

4.3.1.3 SectionProps Class

SectionProps class stores information about geometric properties of sections used in the structure. Two of the geometric variables, which are stored, are the width and height of the sections. Rest of the data is geometric section properties as moment of inertia in both directions, area of the section etc. The aim of implementing this class is to store the fundamental information to be used during constructing of ColType objects.

Member functions implemented in SecitonProps class are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables
- Default Destructor
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables.

4.3.1.4 ColType Class

ColType class is collection of section related data, which are defined in MatType and SectionProp classes. Reinforcement distribution, generation of concrete and steel models, capacity calculations, capacity checks, Moment-Curvature and Interaction relation generations are conducted in this class and all the related information is stored in ColType objects for each type of section used in the building.

The aim of implementing this class is to store the fundamental information to be used during construction of load carrying member objects. The capacity calculation procedures are activated as soon as the model is introduced. During the analyses, capacity checks, placement of hinges and member removal procedures are conducted with this class.

Member functions implemented in ColType class are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables
- Default Destructor
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables, to do some array manipulations and string operations.
- Additional functions: “PrepareSapMatOutput” function is used for preparation of “FRAME SECTION” data block for Sap2000 input file. Some additional functions are used to carry out capacity computations, capacity checks etc.

4.3.1.5 Column, Beam and ShearWall Classes

Column, Beam and ShearWall classes have similar structures. These classes hold information which is related with columns, beams and shear walls. Some of the data stored in objects are:

- Label of member.
- Floor number, where the member is located.
- Length of the member.
- Mass of the member used to compute node masses.
- Grids that the member is located on.
- Section of the member (Coltype object).
- Member end node objects.
- Irregularity:

This information is used to define new location of member, if there is any shift from the predefined grids. The shift is defined with three variables: shift in X direction, shift in Y direction and rotation of member. This property does exist for columns and shear walls.

- Redundant Beams and Nodes:
  - This information is not used with Beams.
  - This information is used with Columns when there is shift in X or in Y direction or both. To simulate shift of member, member is moved to its new location and connected with its previous nodes using rigid links, which are also called redundant beams. This option enables to define columns with eccentricity.
  - In software shear walls can only be defined between two grid intersections with the length defined by the user. Since shear walls are represented by wide column analogy and they are placed in between grid intersections at the middle, the end nodes of the member are connected to the grid intersections with rigid links.
- HingeData:

  HingeData variable holds the results of capacity checks.

  The information stored for both end nodes are as follows:
  - Plastic hinging status of member under flexure in 2-2 direction.
  - Plastic hinging status of member under flexure in 3-3 direction.

Existence of member is the only information stored about the member itself. As explained in Chapter 3, if shear failure take place at any location on member, member is removed form the building by assigning its existence to false.

Member functions implemented in Column, Beam and ShearWall classes are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables.
- Default Destructor.

- Accessor functions: Used to provide accessibility to any encapsulated data (Member variables). Member variables can be modified or called via these functions.
- Additional functions: PrepareSapMatOutput function is used for preparation of “FRAME” data block for Sap2000 input file. Some additional functions are used to carry out capacity checks, initialization of nodes.

4.3.1.6 Node Class

Node class holds information about the nodes, which are generated by use of information gathered from columns, beams and shear walls. The information stored in Node objects is as follows:

- Joint label.
- Grids that the joint is located on.
- Location of the joint.
- Floor number, where the joint is located.
- Mass of the joint:

  This information is gathered by use of beams, columns and shear walls that are connected at the joint under consideration. The mass of each member is distributed among the nodes as follows:

  - For beams: Half of the mass is assigned to two end nodes.
  - For columns: Half of the mass is assigned to two end nodes.
  - For shear walls: Quarter of the mass is assigned to four end nodes.

  Parcel masses are assigned to the parcel master joint. Parcel master joint is located at the geometric center of a parcel and this joint is common for all the shell members in a parcel.

- Joint type information:

  This information is used to distinguish between joints if they are structure, floor or support joints.

The aim of implementing this class is to store the information to be used during constructing of SAP2000 input file, to gather mass information and collect information to be used in automatic shell generation process.

Member functions implemented in Node class are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables
- Default Destructor
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.

4.3.1.7 Floor, Parcel and Shell Classes

Floor class contains information about each floor. Some of the stored data are as follows:

- Floor label.
- Floor number.
- Floor height.
- Floor area.
- Number of floor nodes and Node object addresses (by use of Pointer Technology).
- Parcel information.

Floor class holds Parcel objects. Parcel terminology is used to define closed area by beams or line objects on a floor. Parcel class stores information indicated below:

- Parcel label.
- Parcel floor number.
- Parcel thickness
- Parcel mass.
- Parcel area.
- Material type used for parcel.
- Number of parcel nodes and Node object addresses (by use of Pointer Technology).
- Shell information.

Parcel class holds Shell objects. Shell terminology is used to define segments of parcels. Shell class stores information indicated below:

- Shell label.
- Shell floor number.
- Shell area.
- Shell thickness.
- Shell nodes.

The aim of implementing above-mentioned classes is to store the fundamental information to be used during construction of floor objects. Floor objects, with Parcel and Shell objects, are mainly used for automatic shell generation process. These objects are also used during node mass computation and failure simulation processes.

Member functions implemented in Floor, Parcel and Shell classes are listed below and their brief explanations are presented:

- Constructor: Used initialize the member variables
- Default Destructor

- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables, to do array manipulations, string operations and to gather specific information from objects.
- Additional functions: "PrepareSapShellOutput" function is used for preparation of "SHELL" data block for Sap2000 input file.

4.3.1.8 DisplacementDatabase Class

DisplacementDatabase class is implemented to store node displacements and mode shape displacements. Until the entire pushover procedure is finalized, hundreds of analyses are conducted. In each analysis the displacements must be stored and interconnected with previous information. Some of the data stored in DisplacementDatabase objects are as follows:

- Node label.
- Displacements in global X, Y and Z directions.
- Rotations about global X, Y and Z directions.

Member functions implemented in DisplacementDatabase class are listed below and their brief explanations are presented:

- Constructor: Used to initialise member variables.
- Default Destructor.
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables, to do some array manipulations.
- Additional functions: Used to start generation of node and mode displacement arrays.

4.3.1.9 ForceDatabase Class

ForceDatabase class is implemented to store member end forces and reaction forces. Until the entire pushover procedure is finalized, hundreds of analyses are conducted. In each analysis the member end forces and reaction forces must be stored and interconnected with previous information. Some of the data stored in ForceDatabase objects are as follows:

- Node label.
- Member end forces in global X, Y and Z directions.
- Member end moments about global X, Y and Z directions
- Reaction forces in global X, Y and Z directions
- Reaction moments about global X, Y and Z directions

Member functions implemented in ForceDatabase class are listed below and their brief explanations are presented:

- Constructor: Used to initialise the member variables.
- Default Destructor.
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables, to do array manipulations.
- Additional functions: Used to start generation of member end forces and reaction force arrays.

4.3.1.10 Bina Class

Bina class is the main class that includes all predefined classes as member variables. All the information about the building is stored in this class. The aim of implementing this class is to control the fundamental information to be used by pre-processor, central-processor and post-processor.

Member functions implemented in Bina class are listed below and their brief explanations are presented:

- Constructor: Used to initialise the member variables and to call pre-processor to gather information about the building.
- Default Destructor.
- Accessor functions: Used to provide accessibility to any data (Member variables). Member variables can be modified or called via these functions.
- Helper functions: Used to conduct internal computations to determine member variables, to do array manipulations and string operations.
- Additional functions: The functions that control the interaction of different modules.

4.3.2 Graphical User-Interface Options

User-Interface is designed for Windows operating system. To provide user-friendly environment and help user to switch between options easily, interface is equipped with number of functions. Implemented functions and options are studied in two parts, which are pre-analysis and post-analysis parts. Pre-analysis options ("Part 1" region in Figure 4.1) provide opportunity to the user to modify the structure before analyses easily. Post-analysis ("Part 2" region in Figure 4.1) options provide opportunity the user to evaluate the results directly and easily.

User-interface of Cavas is divided into two main parts. The partitions are displayed in Figure 4.1.

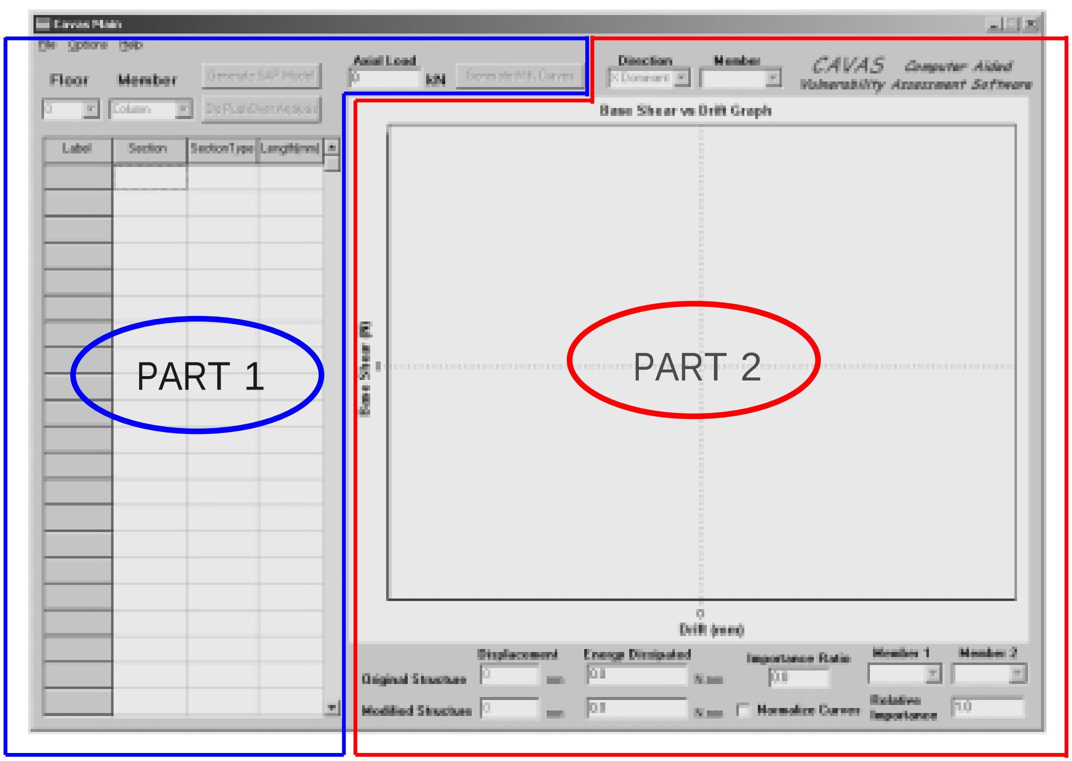

Figure 4.1 Program Environment Partitions

4.3.2.1 Pre-Analysis Options

These options are located at the left side of the environment and collected together for easy usability. At the beginning of the program, some options are disabled. These are still pre-analysis options but they are enabled after the model is introduced to the software. Following are the details of options:

4.3.2.1.1 File Menu

This menu is used to open a model and to exit from the program. When File Menu → Open is clicked classical Windows “Open” menu application is activated which enables user to locate the file easily.

The input file which has special format for CAVAS software must have “.vas” extension. After the file is located and called, input evaluation procedure is activated. This process takes time based on the size and content of the input file. When the evaluation is finalised, all the pre-analysis options are enabled.

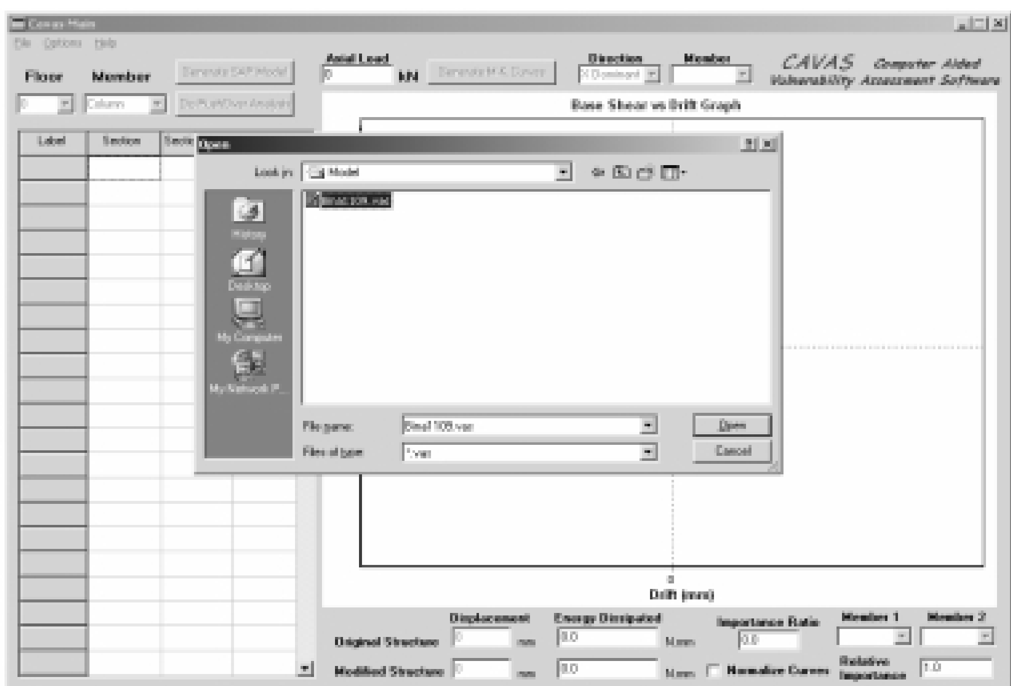

Figure 4.2 Input Calling Window

File Menu → Exit serves to exit from the program.

The open command has another contribution, which is automatically called. This is generation of P-M relations of sections which are defined in the input file. The data are stored in “Excel” format for all sections.

4.3.2.1.2 Member Modification Options

Three facilities, which are circled in Figure 4.3, are used for modification of member section types. After the building is introduced, spreadsheet like part is filled with information about the members (this is demonstrated in Figure 4.3), which are label of the member, section name, section type and length of member. Except “SectionType” column, the remaining data are just for information. User can study the information to check the correctness of input file.

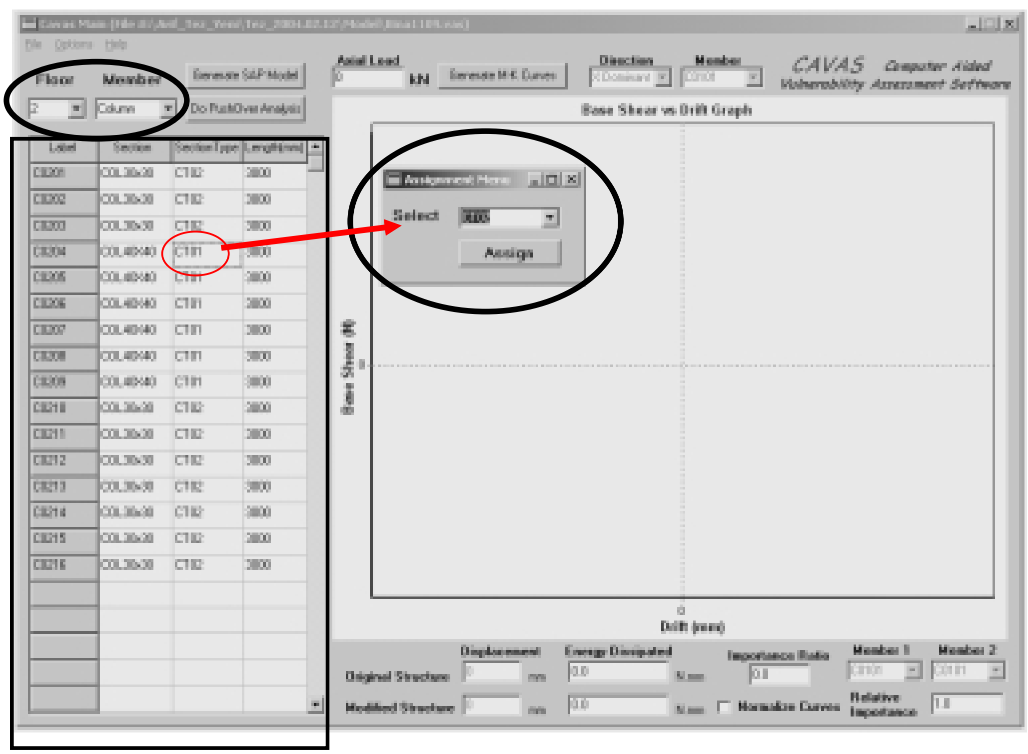

Figure 4.3 Member Modification Options

During preparation of the input file, two different floor plans are used to model the building where the data for second floor contains the differences from first floor in plan. This yields all the members along the height of the building to be same. The “SectionType” column with pull-down menus named “Floor” and “Member” are used to solve this problem. With “Floor” pull-down menu user can study all the floors by choosing appropriate floor number. With “Member” pull-down menu, user can see beams, columns and shear walls separately. After the appropriate floor number and member type are chosen, clicking any cell located on “SectionType” column opens “Assignment Menu” where user can choose original section type and assign it to the member. For this assignment process to work, the section types must be defined in the input file even if they are not used in any of the floor plans.

4.3.2.1.3 Generate SAP2000 Model Option

With this option, user can ask software to prepare SAP2000 input file. When this button is clicked Windows “Save” menu application is activated and the file can be saved at any selected location. Generated file has an extension “.s2k” and contains all the information about the building except reinforcement details. Saved file can be introduced to SAP2000 by import command.

Before starting analysis, it is a good practice to import structure to SAP2000 and study 3D model generated with “Show Extrusions” option enabled, in order to see if the building model is correct.

4.3.2.1.4 Generate M-K Curves Option

This option with the above explained “Generate SAP2000 Model” option, shows two practical areas where the software is used; SAP2000 input file generation and Moment-Curvature data computation. With this option Moment-Curvature relations of the sections defined in the input file are computed. The axial load must be entered to “Axial Load” edit box in “kN”. When the user asks software to prepare Moment-Curvature relations for a specific axial load, the *Moment-Curvature* data, which are computed about strong and weak axes of the section, are stored in “Excel” format for all sections.

4.3.2.1.5 “Cavas Analysis Options” Menu

When “Option Menu” is clicked, “Cavas Analysis Options” menu is displayed. These options are used to conduct analysis with different approaches or to reduce the analysis time, or to avoid unnecessary analyses to be conducted. When the CAVAS is called initially, the options come with the configuration suggested by the author as displayed in Figure 4.4.

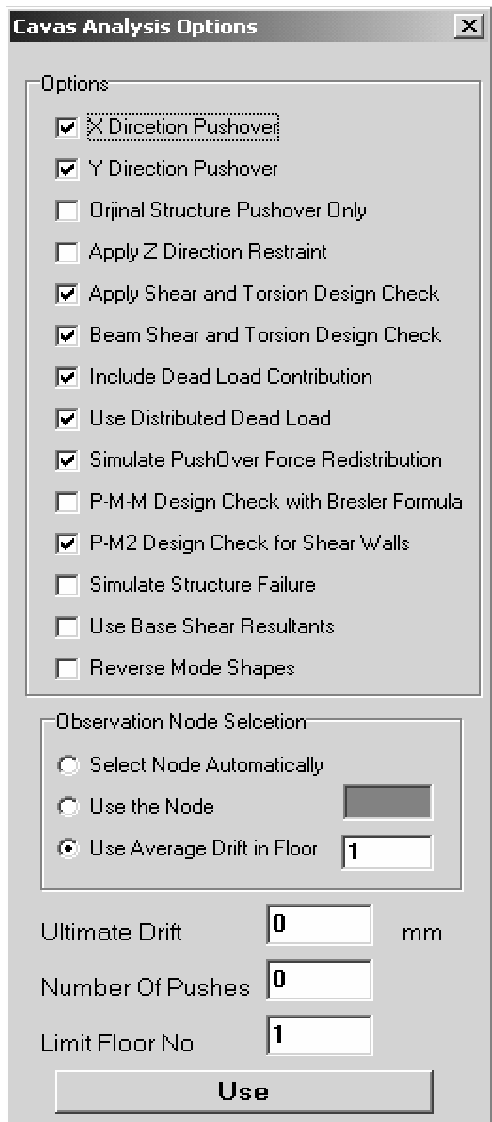

Figure 4.4 Options Menu

The definitions of the options in “Cavas Analysis Options Menu” are as follows:

4.3.2.1.5.1 “X Direction Pushover” Option

This option enables pushover analysis to be conducted for X dominant mode only. Analyses are conducted for original structure and for all the others with member removal process applied.

4.3.2.1.5.2 “Y Direction Pushover” Option

This option enables pushover analysis to be conducted for Y dominant mode only. Analyses are conducted for original structure and for all the others with member removal process applied

4.3.2.1.5.3 “Original Structure Pushover Only” Option

This option enables pushover analysis to be conducted only for the original structure. The direction of the analysis is defined by the options, defined above. If user wants to study the behavior of original structure only, analysis time reduces considerably.

4.3.2.1.5.4 “Apply Z direction Restraint” Option

This option enables structure to be pushed with mode shape taking into consideration Z direction displacements. If this option is not enabled structure is pushed considering only X any Y displacements and Z direction is not restrained.

4.3.2.1.5.5 “Apply Shear and Torsion Design Check” Option

This option enables Shear and Torsion Design Checks to be applied all members during capacity check process. With this option disabled shear and torsion failures will be disregarded.

4.3.2.1.5.6 “Beam Shear and Torsion Design Check” Option

This option enables Shear and Torsion Design Check to be applied beams. If “Apply Shear and Torsion Design Check” is disabled, then this option has no effect.

4.3.2.1.5.7 “Include Dead Load Contribution” Option

This option enables dead load contribution to be considered in the analysis. If disabled dead load contribution will be disregarded during analysis.

4.3.2.1.5.8 “Use Distributed Dead Load” Option

This option enables floor dead load to be distributed on beams. If disabled, floor dead loads are directly applied to columns. Enabling this option is suggested. If “Include Dead Load Contribution” is disabled, then this option has no effect.

4.3.2.1.5.9 “Simulate Pushover Force Redistribution” Option

This option enables the activation of procedure “Do Force Redistribution” described in section 2.2.3.17.

4.3.2.1.5.10 “P-M-M Design Check with Bresler’s Formula” Option

This option enables Bressler formula to be applied druing axial load & moment capacity check. If disabled simpified method suggested by the author will be applied. The details of the design checks are descrkibed in Chapter 3

4.3.2.1.5.11 “Simulate Sturctural Failure” Option

This option enables simulation of structural failure scheme. The details of structural failure implementation is explained in detail in Appendix A.

4.3.2.1.5.12 "Use Base Shear Resultants" Option

In each step of pushover analyses, total base shear in global X and Y directions are computed and used in pushover curve generation. This option enables base shears to be computed as resultants of shear forces in X and Y directions. If disabled, for X and Y direction pushovers, summation of base shears in X ad Y directions will be computed, respectively.

4.3.2.1.5.13 "Ultimate Drift" Edit Box

Ultimate displacement of the observation node is entered in this box. When ultimate displacement is reached, analysis ends even if the failure does not take place.

4.3.2.1.5.14 "Number Of Pushes" Edit Box

Number of steps to reach ultimate displacement is entered in this box. The size of each increment is determined by taking ratio of ultimate displacement to the number of pushes. The value entered determines the accuracy of the results.

4.3.2.1.5.15 "Limit Floor No" Edit Box

During member importance evaluation analyses, the columns and the shear walls to be removed from the building are determined with the value entered in this box. Only the members which are located below the entered floor are removed one by one form the building.

4.3.2.1.5.16 "Use" Button

This button finilize the option selection process and stores data to be used in the analyses.

4.3.2.2 Post-Analysis Option

Post-Analysis options are located at the right side of the environment and collected together for easy usability. At the beginning of the program, all post-analysis options are disabled. Following are the details of options:

4.3.2.2.1 Chart Tool

Chart is very effective tool to present the results of the analyses. On the chart, horizontal axis represents Displacement of the observation joint in “mm”. Vertical axis represents total base shear in “N”. After the analyses are finalized the pushover curves are plotted on this chart. As seen in the Figure 4.5 the top curve is for original structure and bottom curve is for building for which one of the members is removed.

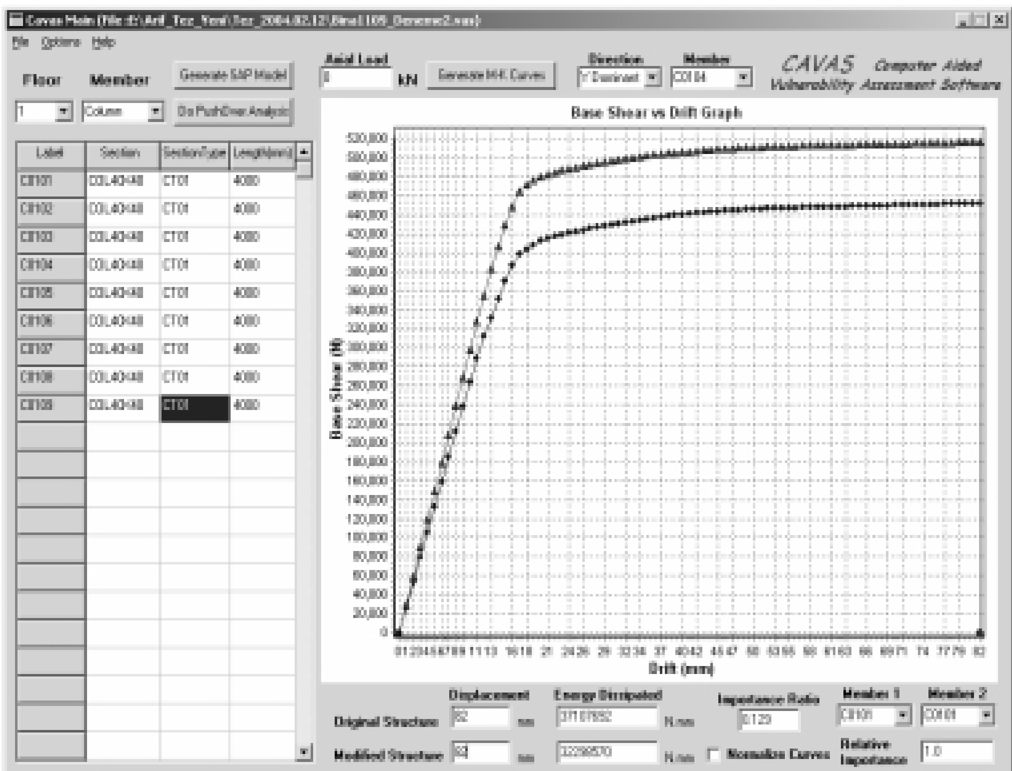

Figure 4.5 Chart Tool View

The options used to control the chart are as follows:

4.3.2.2.2 "Direction" Pulldown Menu

This menu enables to switch between results of X and Y dominant pushover analyses. With this option the behavior of structure in both directions is studied easily.

4.3.2.2.3 "Member" Pulldown Menu

This menu enables to switch between results of pushover analysis for the removed members. The chosen member indicates the structure with the chosen member removed. With this option the effect of removal of each member on the original structure is studied easily.

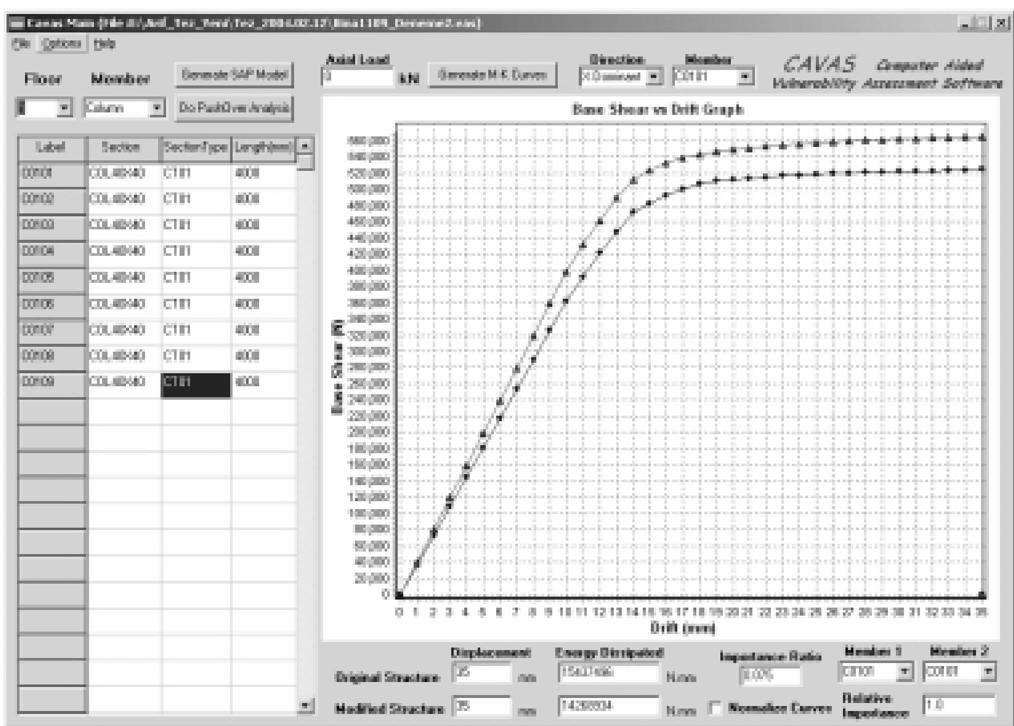

Figure 4.6 Example Pushover Results in X Dominant Direction for the Case Member C0101 is removed.

4.3.2.2.4 Displacement Data for Original and Modified Structure

The results of displacement based pushover analyses are open to discussion because during the analyses even if the 90% of the load carrying memebers were failed under flexure, the structure keeps its stability for a while. Figure 4.7 shows an example of this fact. The resuts indicate that the modified structure behaved more ductile than the original structure. This comment is not wrong but as far as the importance concept is considered the result may lead to misleading results also. Beacause there are some situations that the modified structure displaces 1.5 times the original structure due to reduction in stiffness.

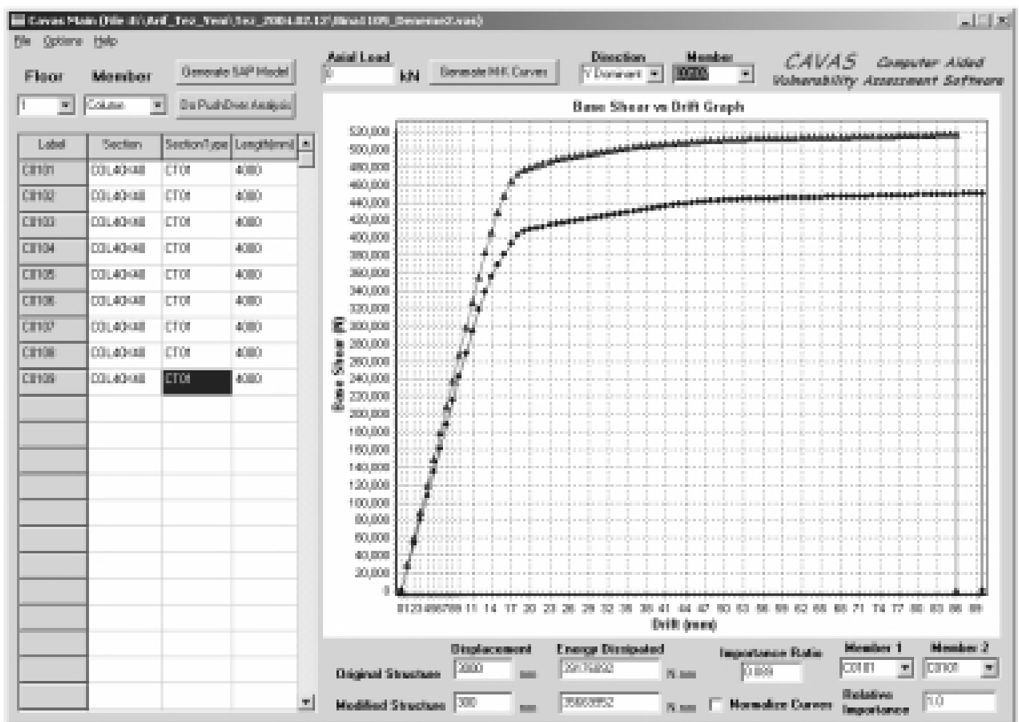

Figure 4.7 Example Pushover Results for Displacement Comparison

Therefore, to see the effect of member removal on the plastic behavior of the building, this option is implemented to enable user to change final displacement values for original and modified structures. These edit boxes arranges the displacement limits of the curves. If the data in these edit boxes are changed, the curves are arranged so that the final displacement value is equal to the entered value. Initially, if the curve does not extend to the entered value, it keeps its original layout.

4.3.2.2.5 “Normalize Curves” Check Box

This check box is used to normalize every curve with respect to original curve. When this check box is enabled, the curves which are shorter are extended through the maximum displacement of original structure and the curves which are longer are cut at maximum displacement of original structure.

4.3.2.2.6 “Energy Dissipated” Edit Boxes

There are two edit boxes that show energy dissipated by original structure and by modified building. Detailed information about this topic is given in Chapter 2.

4.3.2.2.7 “Importance Ratio” Box

This edit box shows the result of importance calculation for the selected member. Detailed information about importance concept is given in Chapter 2.

4.3.2.2.8 “Relative Importance” Box

This edit box shows the result of relative importance calculation for the selected members. Detailed information about relative importance concept is given in chapter 2.

Pull down boxes, titled as “Member1” and “Member2” enables user to change members to see relative importance of two members.

CHAPTER 5

APPLICATIONS

5.1 INTRODUCTION

In this chapter, member importance factor concept and computation procedures are presented. Proposed method is applied to 4 buildings and the results are demonstrated. The verification of the CAVAS software is conducted using commercially available analysis software. Following the verification stage, the application cases and analyses results are presented.

5.2 SOFTWARE VERIFICATION

Before conducting vulnerability index computation analyses with CAVAS, software is tested with SAP2000 for verification. Verification studies are conducted for two different buildings. First test building is symmetric in both directions and the results show the validity of CAVAS. The results of the comparison for the first building are presented in Appendix B. In order to test the applicability of CAVAS for irregular buildings, second verification test is conducted on a building with the following properties and the results are presented in this chapter.

- Details of the sections used in building are displayed in Figures 5.1 to 5.4.
- Building has 2 stories and 2 bays in each direction. 3D Model of building and floor plans are displayed in Figures 5.5 to 5.9.
- First floor height: 4m and second floor height: 3m.
- Building has plan and elevation irregularities.

5.2.1 Verification Procedure

The verification procedure is as follows:

1. Building input file is prepared for CAVAS using its own input file format. The SAP2000 input file generated by CAVAS is used for push over analysis in SAP2000 to avoid any modeling differences.
2. X and Y direction dominant pushover analyses are conducted by CAVAS with 1mm increments. The results obtained by CAVAS are displayed in Figures 5.10 and 5.11 for X and Y directions, respectively.
3. For X and Y directions, two different pushover load cases are defined in SAP2000. For X direction pushover load case, X direction dominant mode determined by CAVAS is used. Similarly for Y direction pushover load case, Y direction dominant mode determined by CAVAS is used.
4. Reinforcement details are entered to SAP2000 program manually.
5. In SAP2000 hinge properties of columns and beams are defined as follows: For columns, user defined "PMM" hinges and for beams, user defined "M3" hinges are used. For both hinge types, elastoplastic moment-rotation relations are defined. Column interaction surface computation is carried out by "Concrete ACI 318-95" option, in SAP2000.
6. Displacement based pushover analyses are conducted with SAP2000 for two models using two pushover load cases. The results of pushover analyses in X and Y directions are displayed in Figures 5.12 and 5.13, respectively.

In CAVAS elastoplastic model is used for steel. The model variables are as follows:

- $\varepsilon_{sy} = 0.0021$ where $f_{sy} = 420$ Mpa
- $\varepsilon_{sh} = \varepsilon_{su} = 0.1$

The explanation of the steel model variables is presented in Section 3.2.1.2.

Details of the section types used in building are shown in Figures 5.1 to 5.4. Table 5.1 shows a list of all members with assigned section types for test building.

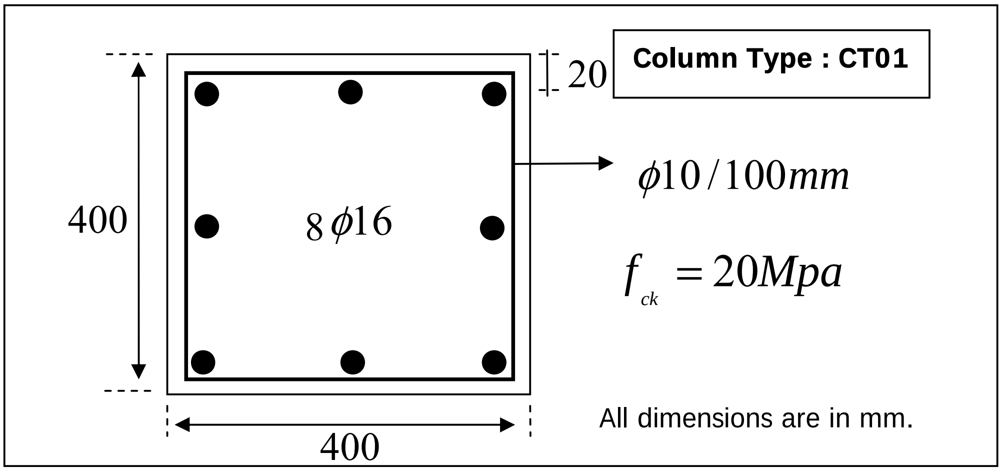

Figure 5.1 Details of Column Type CT01

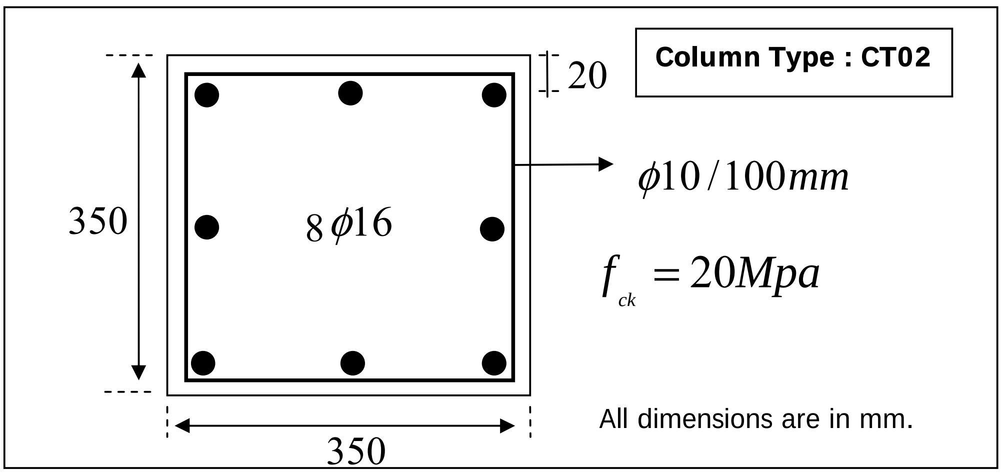

Figure 5.2 Details of Column Type CT02

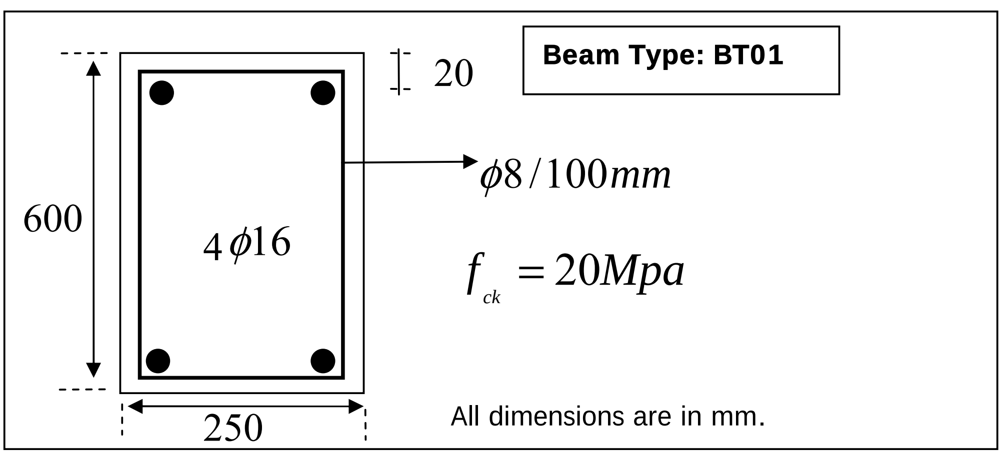

Figure 5.4 Details of Beam Type BT01

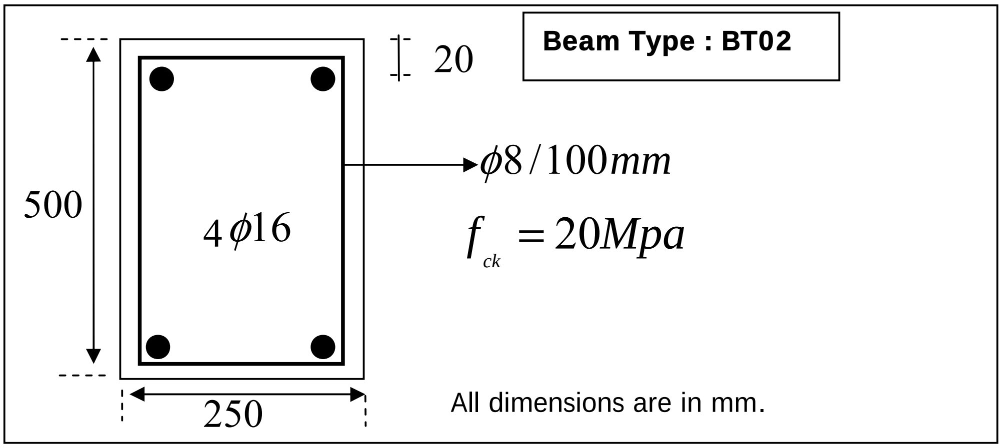

Figure 5.3 Details of Beam Type BT02

Table 5.1 List of Members with assigned Section Types

1st Floor Beams	
Member Label	Section Type
B0101	BT01
B0102	BT01
B0103	BT02
B0104	BT02
B0105	BT01
B0106	BT01
B0107	BT01
B0108	BT02
B0109	BT02
B0110	BT02
B0111	BT02
B0112	BT02
B0113	BT02
B0114	BT01
B0115	BT01
B0116	BT01
B0117	BT02
B0118	BT02
B0119	BT01
B0120	BT01
B0121	BT01
B0122	BT02
B0123	BT02

2nd Floor Beams	
Member Label	Section Type
B0201	BT01
B0202	BT01
B0203	BT02
B0204	BT02
B0205	BT01
B0206	BT01
B0207	BT01
B0208	BT02
B0209	BT02
B0210	BT02
B0211	BT02
B0212	BT02
B0213	BT02
B0214	BT01
B0215	BT01
B0216	BT01
B0217	BT02
B0218	BT02
B0219	BT01
B0220	BT01
B0221	BT01
B0222	BT02
B0223	BT02

1st Floor Columns	
Member Label	Section Type
C0101	CT01
C0102	CT01
C0103	CT01
C0104	CT01
C0105	CT01
C0106	CT01
C0107	CT01
C0108	CT01
C0109	CT01

2nd Floor Columns	
Member Label	Section Type
C0201	CT01
C0202	CT01
C0203	CT01
C0204	CT01
C0205	CT01
C0206	CT01
C0207	CT01
C0208	CT01
C0209	CT01
C0210	CT02
C0211	CT02
C0212	CT02
C0213	CT02
C0214	CT02
C0215	CT02
C0216	CT02

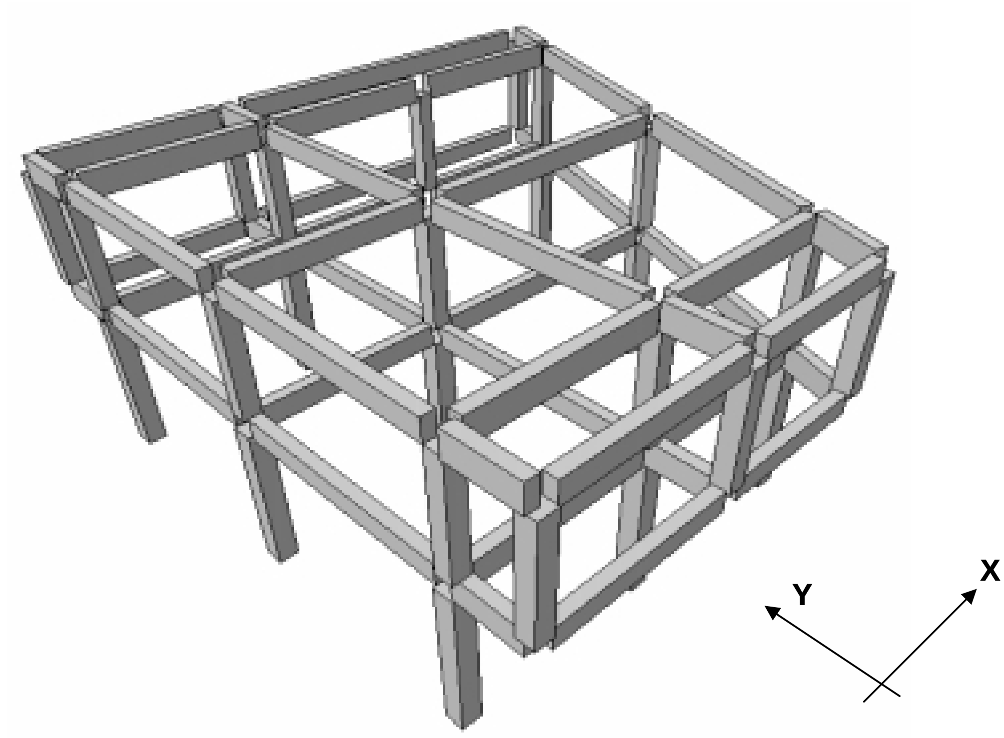

Figure 5.5 3D Model of Test Building

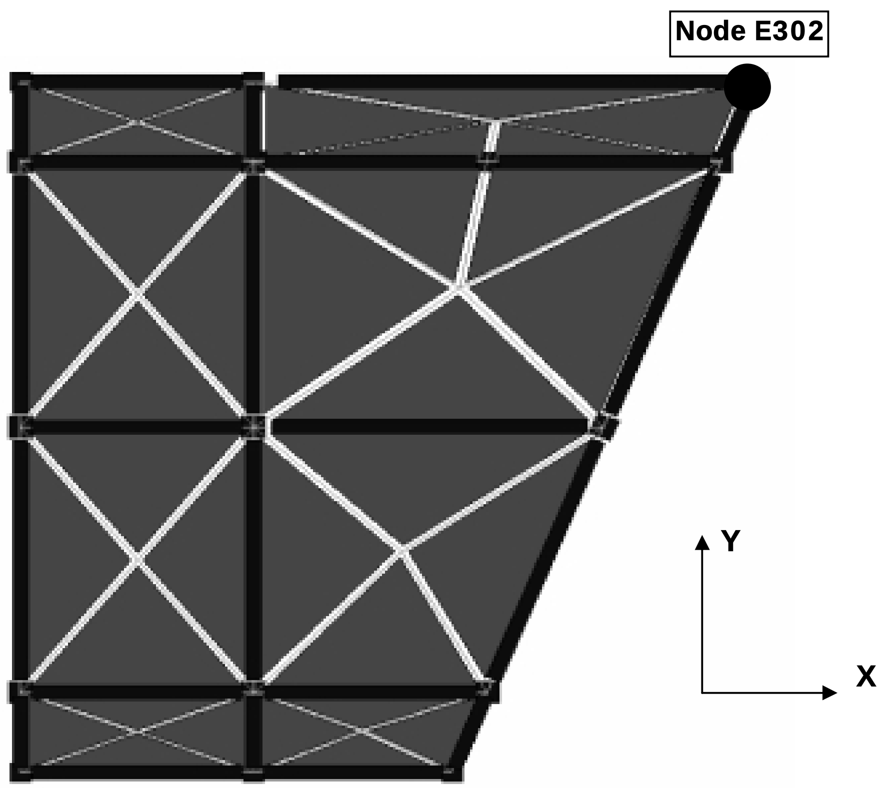

Figure 5.6 Floor Plan of Test Building with Shells

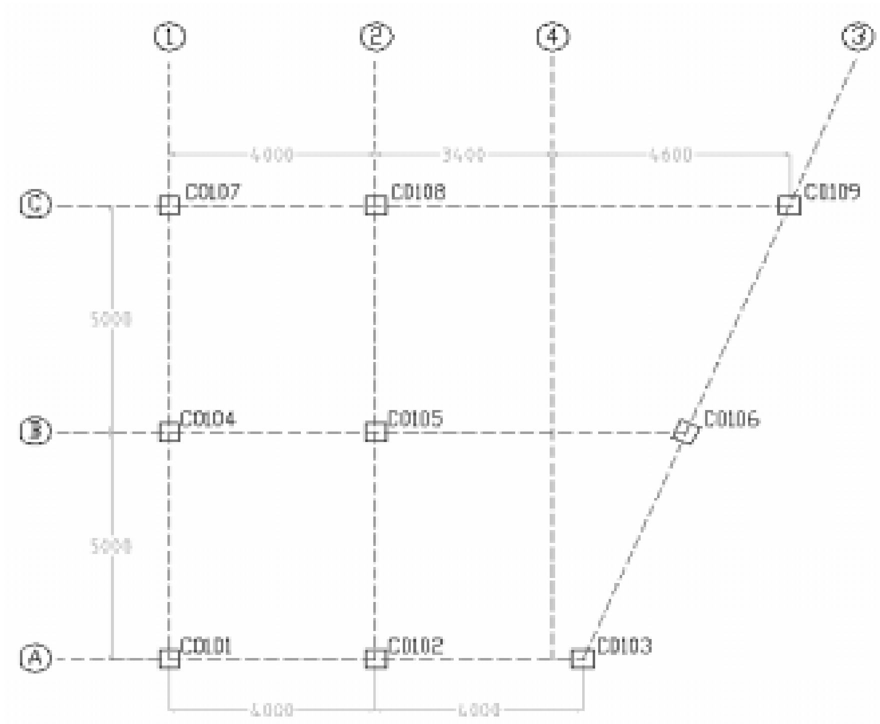

Figure 5.7 Base Plan of Test Building

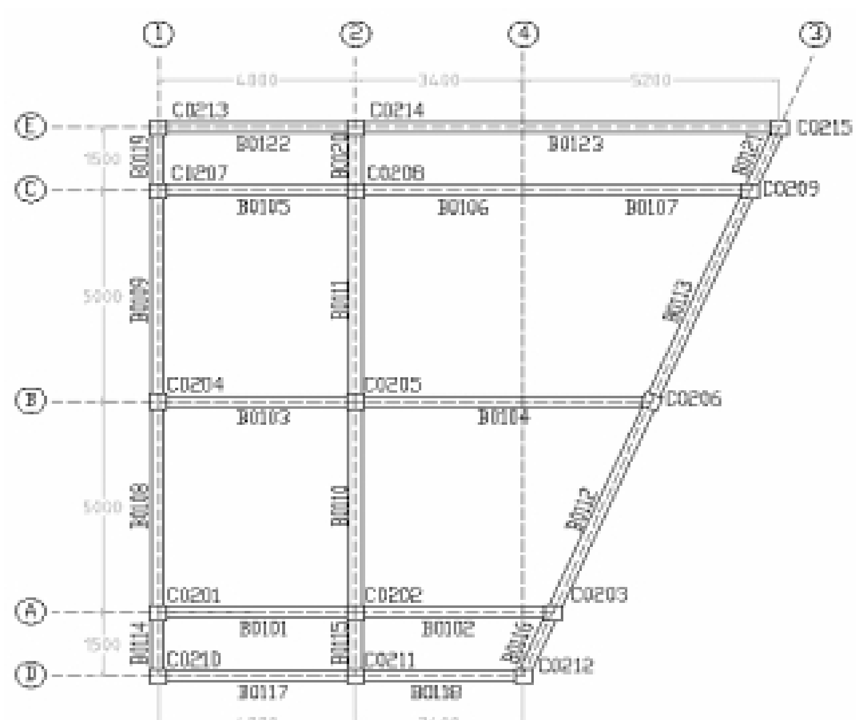

Figure 5.8 1st Floor Plan of Test Building

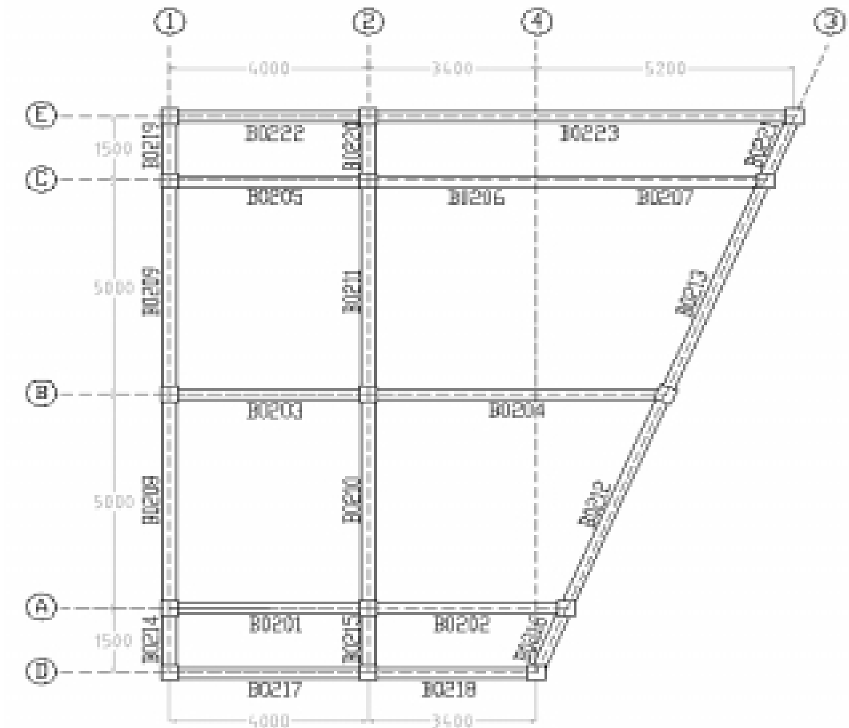

Figure 5.9 2nd Floor Plan of Test Building

5.2.2 Discussion of Pushover Analyses Results

The pushover curves obtained by CAVAS are displayed in Figures 5.10 and 5.11 for X and Y directions, respectively. The pushover curves obtained by SAP2000 are displayed in Figures 5.12 and 5.13 for X and Y directions, respectively. Graphs prepared for comparison of the results are displayed in Figures 5.14 and 5.15 for X and Y directions, respectively.

The aim of applying verification analyses is to check the consistency of results obtained by both software. As the graphs are studied, the consistency on the results is clearly observed. Careful examination of the curves shows two minor differences:

1. Small discrepancy at yielding portion of the curves.
2. Small discrepancy at the (maximum) drift values where the failure mechanisms are formed.

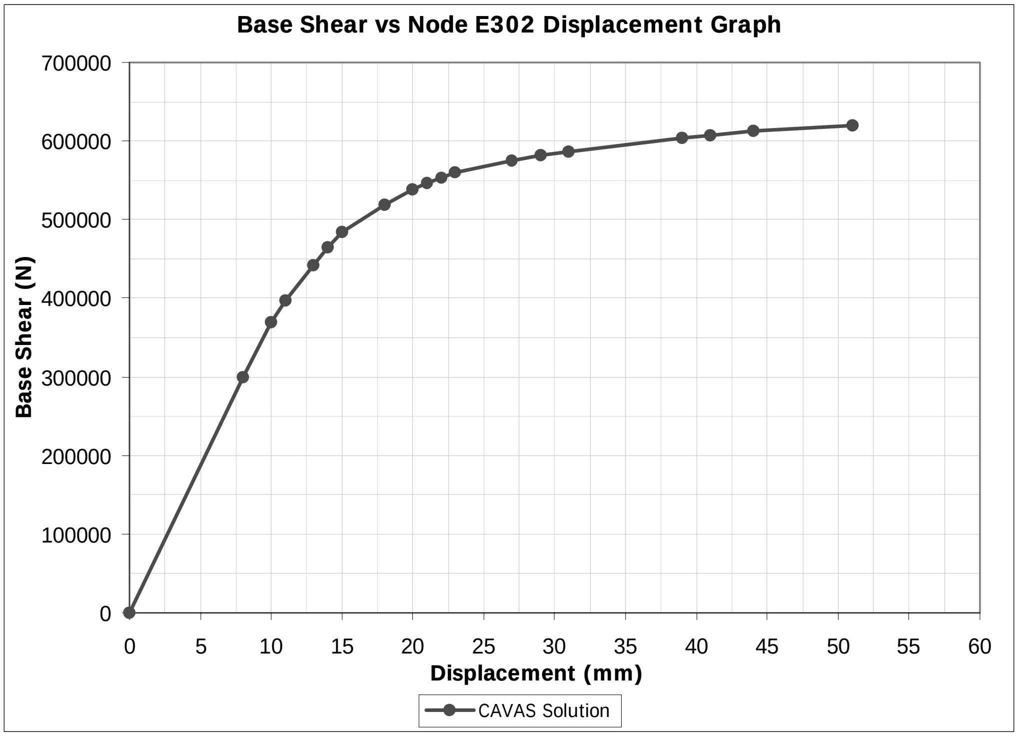

Figure 5.10 CAVAS Pushover analysis result conducted in X Direction

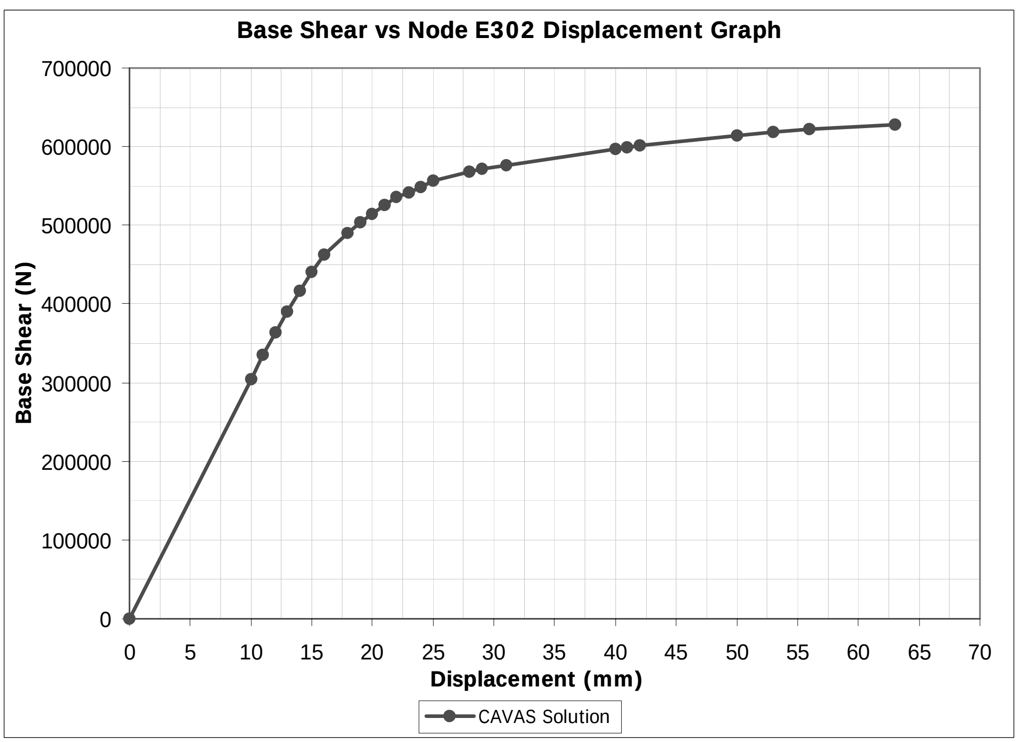

Figure 5.11 CAVAS Pushover analysis result conducted in Y Direction

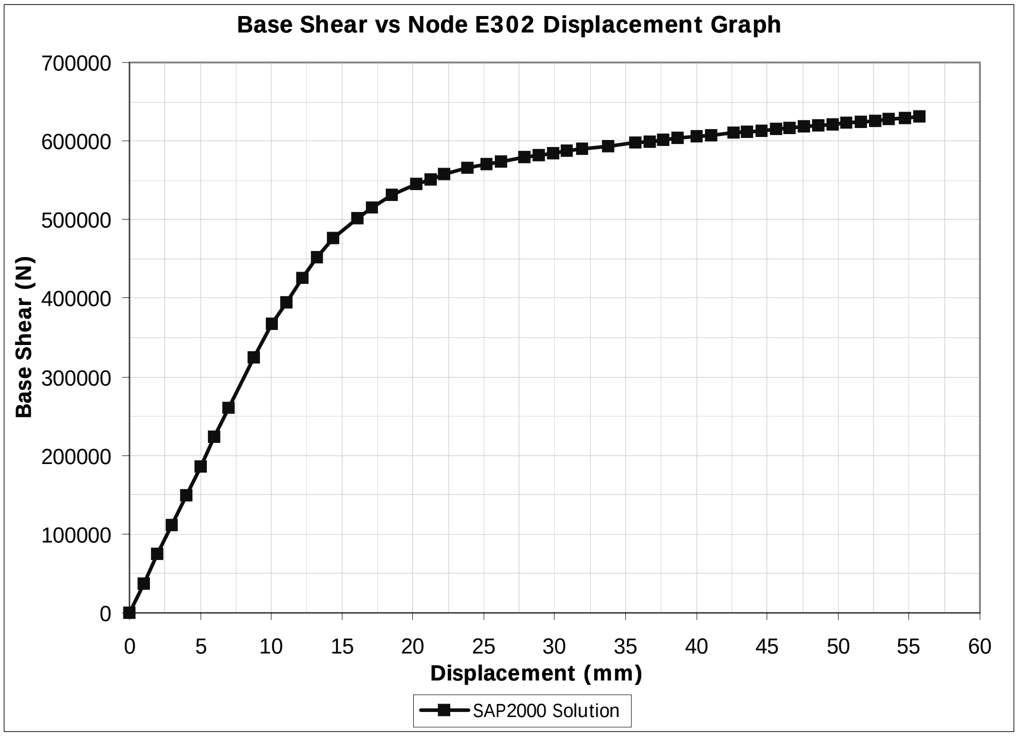

Figure 5.12 SAP2000 Pushover analysis result conducted in X Direction

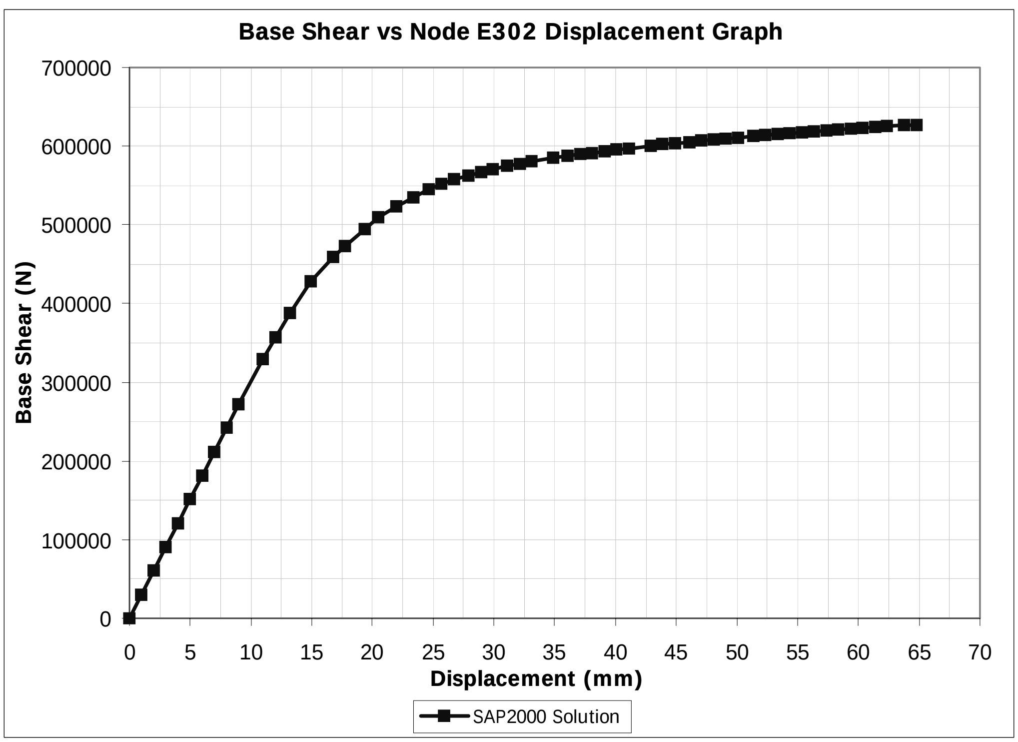

Figure 5.13 SAP2000 Pushover analysis result conducted in Y Direction

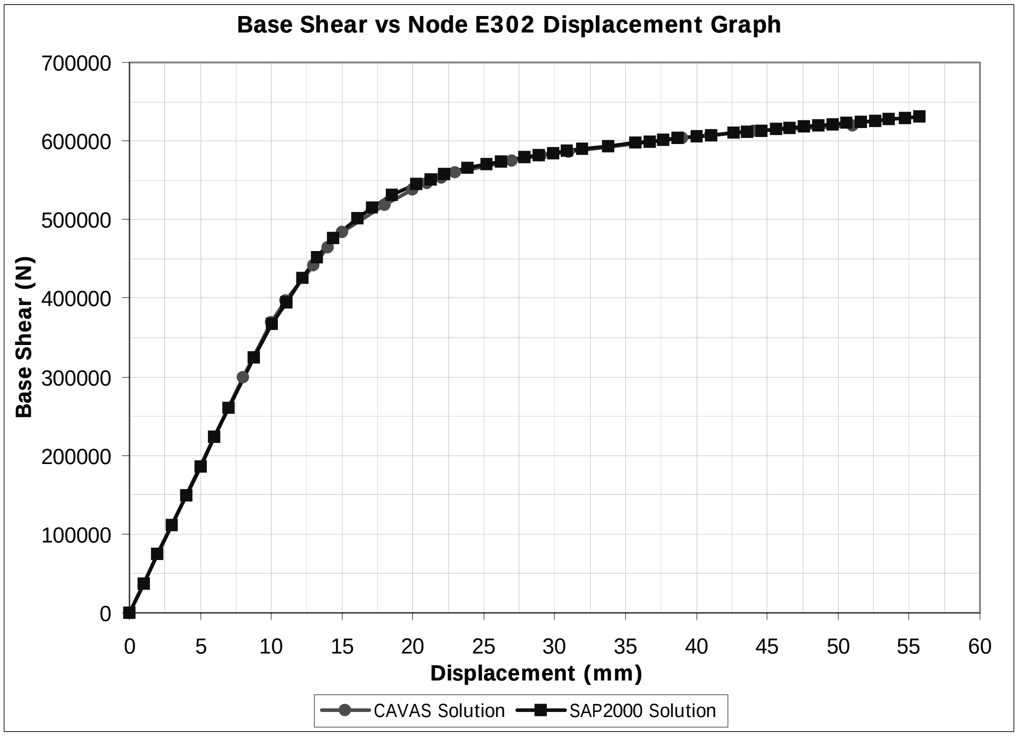

Figure 5.14 Pushover Curves obtained by CAVAS and SAP2000 in X Direction

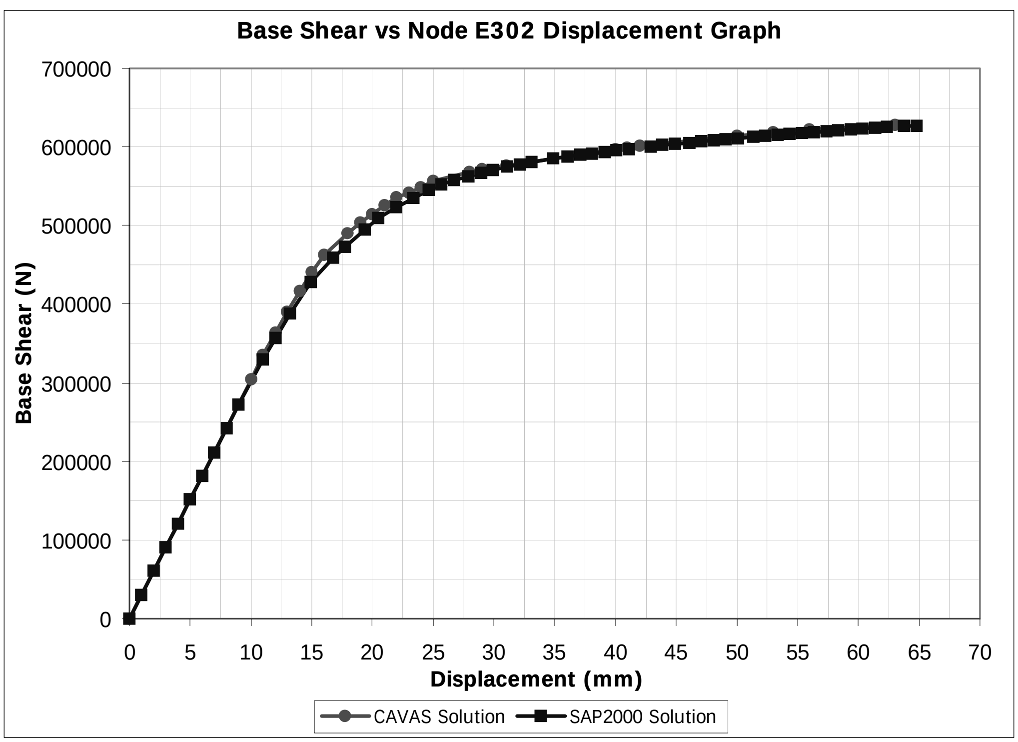

Figure 5.15 Pushover Curves obtained by CAVAS and SAP2000 in Y Direction

The minor discrepancies mentioned above are primarily based on the capacity calculation procedures implemented in two different software (i.e., SAP2000 and CAVAS). Since shear failures are disregarded during verification analyses in CAVAS, the sequence of plastic hinge formation determines the slope of the curve after the first yielding point. For CAVAS, implemented behavior for sections subjected to axial load and biaxial moments are described in section 3.2.3.2. In Sap2000, the behavior of the sections subjected to axial load and biaxial moments are determined by assigned hinge properties. Defined hinge properties for the verification buildings are given in 5.2.1.

Pushover analyses of CAVAS end due to one of the reasons indicated below:

1. Local stability might be lost (see Appendix A).
2. Overall stability might be lost (global mechanism formation).

For test buildings, overall stability is lost due to formation of plastic hinges at both ends of all base columns. CAVAS analyses stops when such a stability problem is encountered. With SAP2000, analyses continue even if the hinge formation takes place at both ends of base columns due to bi-linear moment-rotation definition. Although the post-yielding slope is defined very small, the SAP2000 analysis continues does not stop when all column hinges are formed. For consistency during comparisons, SAP2000 pushover curve is plotted until the drift level at which plastic hinges are formed at both ends of the base columns.

The consistency of the results obtained by two software (see Figures 5.14 and 5.15) is observed. Therefore, it is concluded that the pushover module implemented in CAVAS gives reasonable results.

The evaluation of different buildings with CAVAS will be presented in the following section.

5.3 IMPORTANCE FACTOR CALCULATIONS

In this section, main assumptions made for importance factor calculation method are emphasized (see 2.2.3.5) and proposed procedure is applied on two different buildings. To show the effect of member locations and section properties on the importance factors, first building is analyzed for 3 different member layouts (shear wall and column locations are changed between each one of the three models). Second building has shear walls and wide columns. This building is good example to demonstrate the effects of shear walls and wide columns on the structural behavior. Second building is also used for the beam importance analyses.

The importance factor concept is the basis of vulnerability index and assessment calculation procedures in general. The importance factors assigned to structural members are usually determined by common sense/experience. In this study, however, the importance factors assigned to members are determined based on non-linear analyses and in a methodological way by removing each member and numerically evaluating its effect on the structure. For each case, pushover analyses are conducted in positive and negative directions using the newly calculated mode shapes for each loading step to calculate member importance factors. Largest of the member importance factors calculated in both directions (i.e., + and – direction) is used in vulnerability index calculation process for each mode direction (i.e., x or y direction). In this section, the proposed mathematical method that calculates member wise importance factors will be explained using four examples.

Main assumption made in this method is "Importance of a member is linearly proportional with its contribution to energy dissipation capacity of the structure." Member importance factor calculation using earthquake records is possible. On the other hand, selection of which earthquake data is a dilemma. Using a large number of records or generated earthquake data is simply not practical. The other alternative is using design response spectra, which is also an inferior method since the analysis is linear. As a better alternative, member importance factors are determined using pushover analyses, which is a very powerful tool that incorporates non-linear behavior and determines the capacity curve of a building.

The proposed method enables determination of importance factor of each individual member specific to each different building (e.g., same member in a different building or at a different location in the same building would have a different importance factor). In this way, standardized importance factors are not used for all buildings, but customized member importance evaluation is conducted based on the geometry, member distribution, and similar factor of a given building. Some vulnerability index calculation procedures use information related with floors areas, total member cross section areas, and existence of some deficiencies (such as short columns, plan irregularities etc.). Total member areas and floor areas may be similar for different buildings, but structural system layout, collapse mechanisms and as a result, the seismic vulnerability indices may be completely different.

For buildings, member importance factors are computed with 2 different approaches. These are:

1. Elastic Approach: In this approach, the importance factors are computed by taking the ratio of shear force applied to each column to the total base shear. This evaluation procedure is applied to see if the elastic responses of the members can be used instead of the proposed method. This evaluation is conducted by using elastic range of pushover curves.
2. Plastic Approach: In second evaluation the importance factors are computed based on energy concept using inelastic behavior of buildings as described in section 5.3.

The application of the method on evaluation of 4 different buildings is presented in the following sections.

During analyses following capacity check procedures are used:

1. Shear & Torsion failure is enabled (see section 4.3.2.1.5.5).
2. P-M-M design check which is proposed by the author is used (see section 3.2.3.2).
3. “Failure Simulation” is disabled (see section 4.3.2.1.5.11).

5.3.1 BUILDING 1

Test building, for which the details are given in Figures 5.5 to 5.9, is modified and evaluated in this section. All second floor column section types are changed to CT02, which is a smaller section, using the change utility of CAVAS. The revised list of members with assigned section types are presented in Table 5.2.

Table 5.2 List of Members with assigned Section Types for Building 1

1st Floor Beams	
Member Label	Section Type
B0101	BT01
B0102	BT01
B0103	BT02
B0104	BT02
B0105	BT01
B0106	BT01
B0107	BT01
B0108	BT02
B0109	BT02
B0110	BT02
B0111	BT02
B0112	BT02
B0113	BT02
B0114	BT01
B0115	BT01
B0116	BT01
B0117	BT02
B0118	BT02
B0119	BT01
B0120	BT01
B0121	BT01
B0122	BT02
B0123	BT02

2nd Floor Beams	
Member Label	Section Type
B0201	BT01
B0202	BT01
B0203	BT02
B0204	BT02
B0205	BT01
B0206	BT01
B0207	BT01
B0208	BT02
B0209	BT02
B0210	BT02
B0211	BT02
B0212	BT02
B0213	BT02
B0214	BT01
B0215	BT01
B0216	BT01
B0217	BT02
B0218	BT02
B0219	BT01
B0220	BT01
B0221	BT01
B0222	BT02
B0223	BT02

1st Floor Columns	
Member Label	Section Type
C0101	CT01
C0102	CT01
C0103	CT01
C0104	CT01
C0105	CT01
C0106	CT01
C0107	CT01
C0108	CT01
C0109	CT01

2nd Floor Columns	
Member Label	Section Label
C0201	CT02
C0202	CT02
C0203	CT02
C0204	CT02
C0205	CT02
C0206	CT02
C0207	CT02
C0208	CT02
C0209	CT02
C0210	CT02
C0211	CT02
C0212	CT02
C0213	CT02
C0214	CT02
C0215	CT02
C0216	CT02

The X and Y dominant mode shapes used in the pushover analyses are displayed in Figures 5.16 and 5.17, respectively. The pushover curves obtained in X and Y directions are presented in Figures 5.18 to 5.35. Two example curves, which are used in elastic approach, are shown in Figures 5.36 and 5.37.

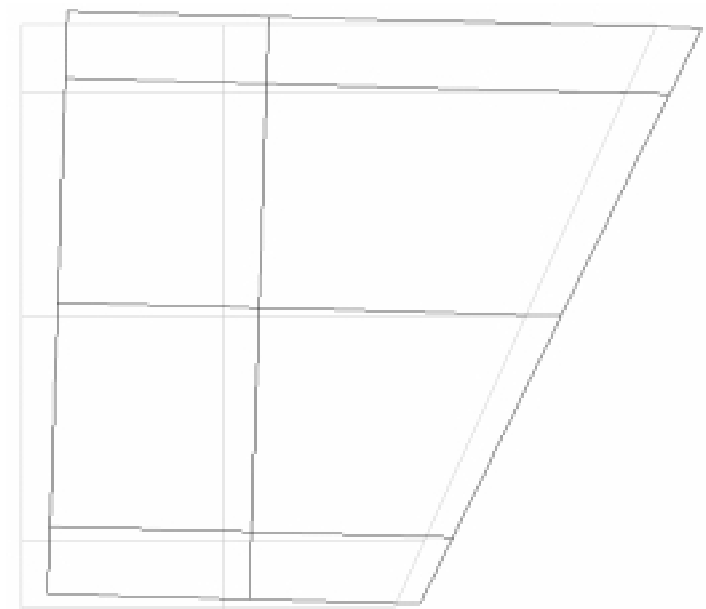

Figure 5.16 Mode Shape in X Dominant Direction for Building 1

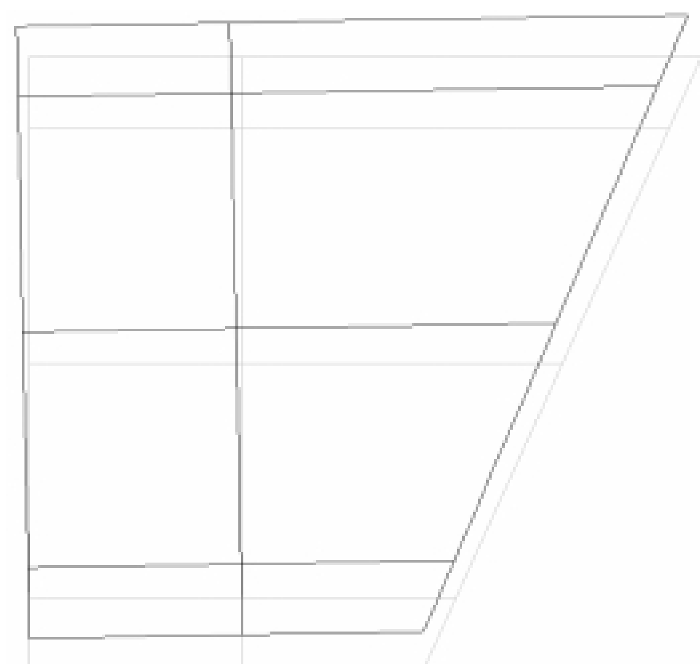

Figure 5.17 Mode Shape in Y Dominant Direction for Building 1

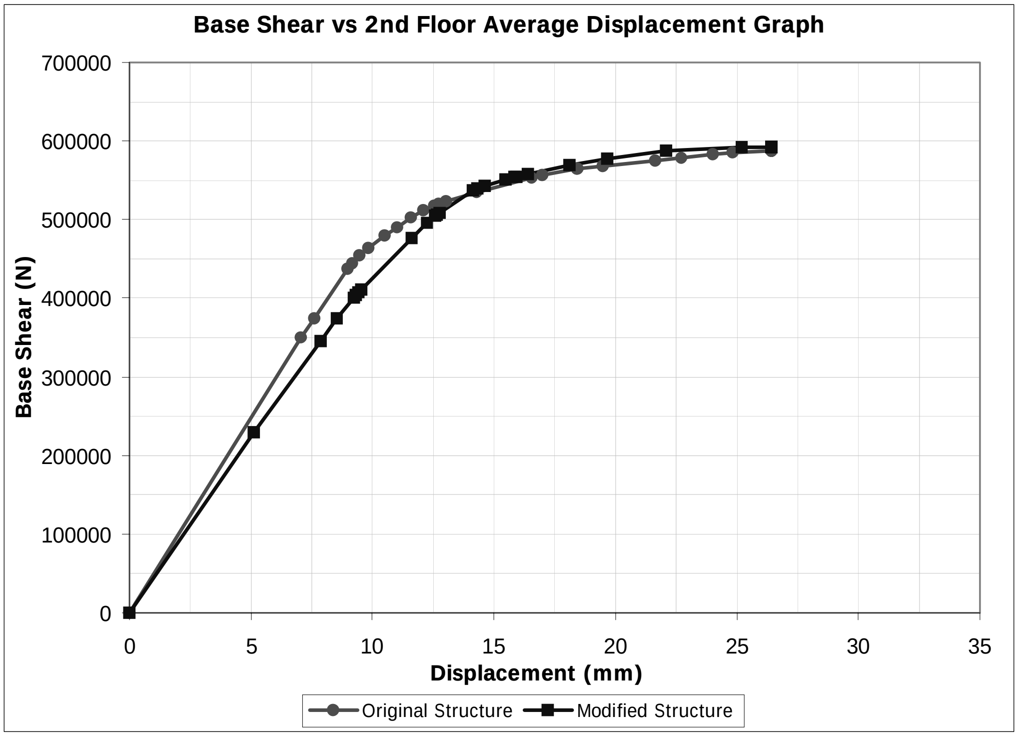

Figure 5.18 (-) X Direction Pushover for Building 1. Removed Member: C0101

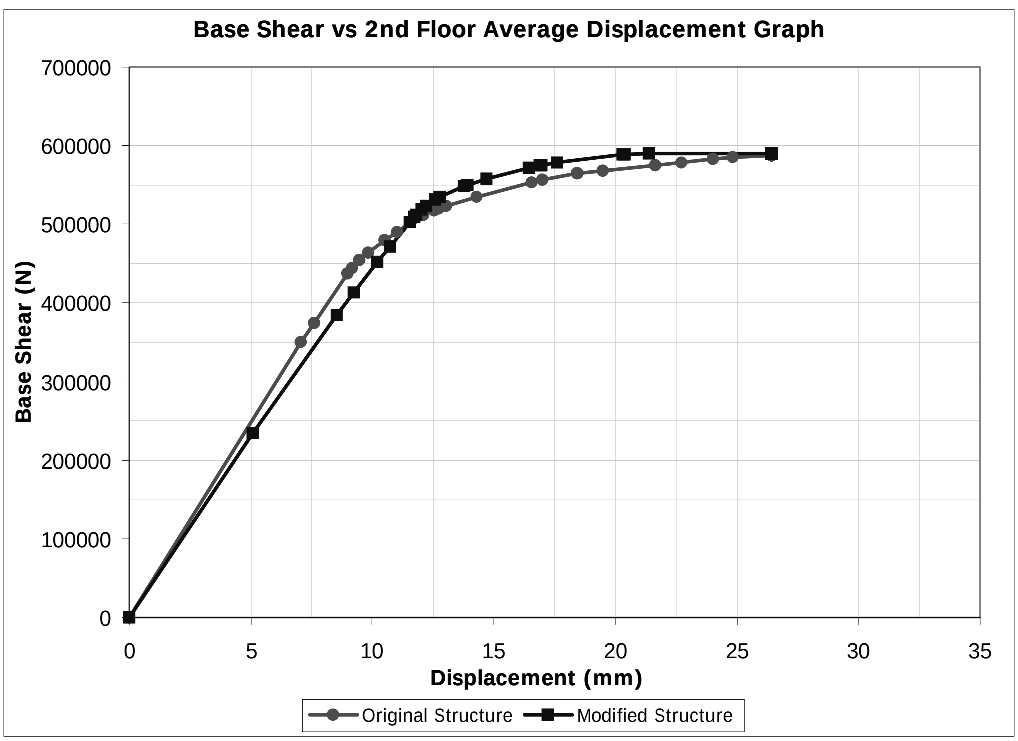

Figure 5.19 (-) X Direction Pushover for Building 1. Removed Member: C0102

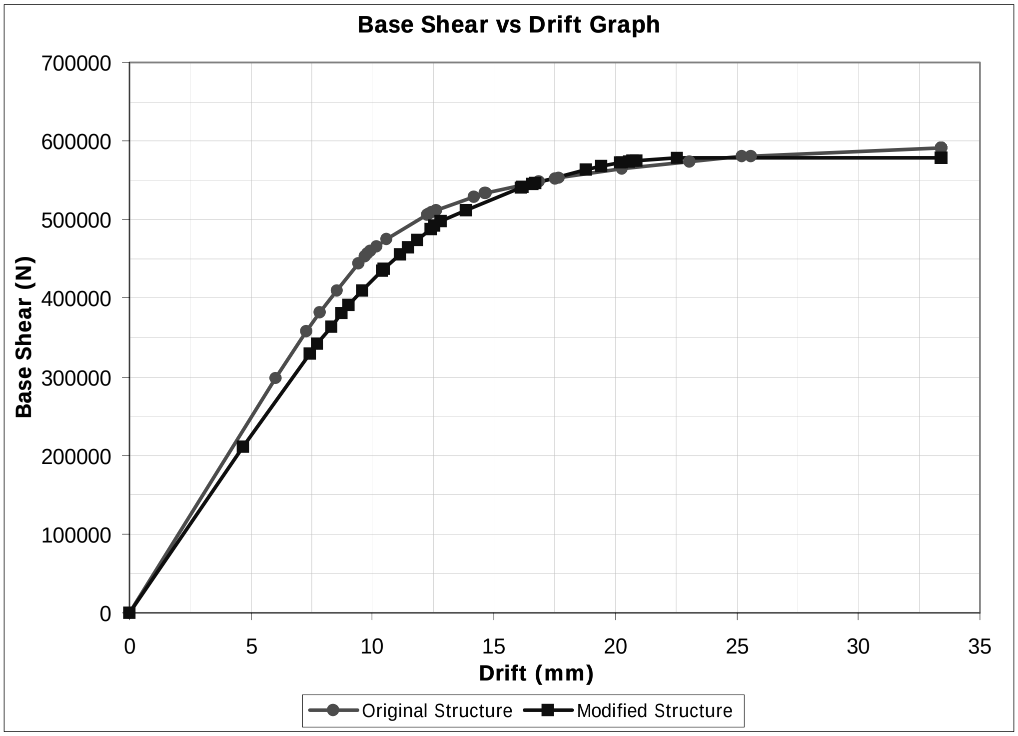

Figure 5.20 (+) X Direction Pushover for Building 1. Removed Member: C0103

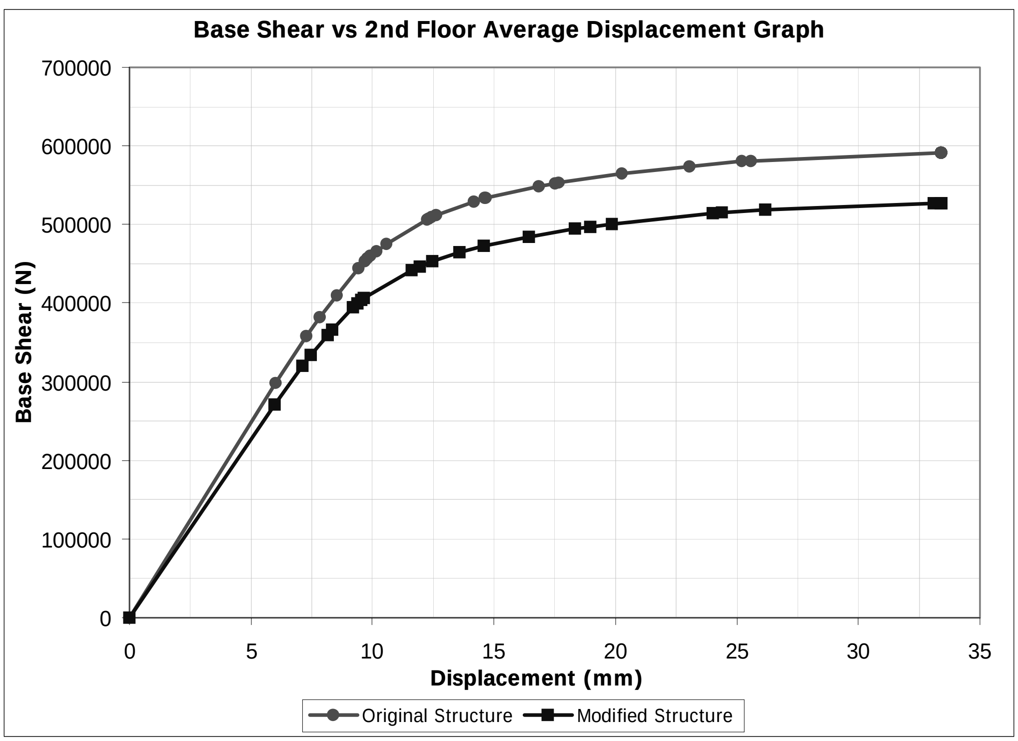

Figure 5.21 (+) X Direction Pushover for Building 1. Removed Member: C0104

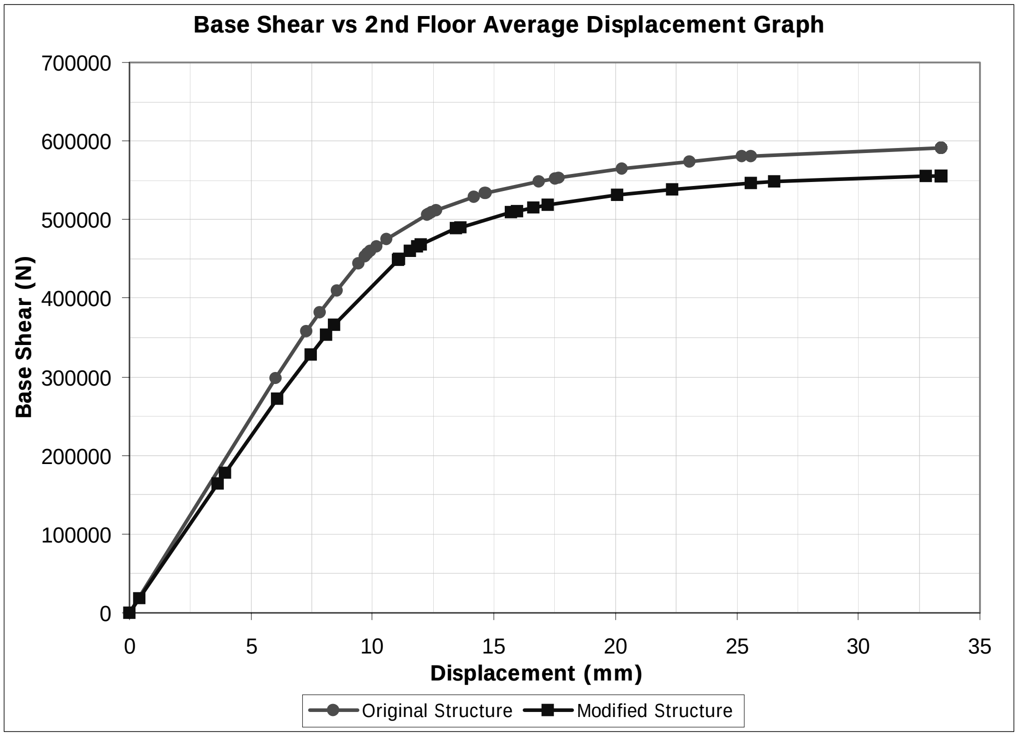

Figure 5.22 (+) X Direction Pushover for Building 1. Removed Member: C0105

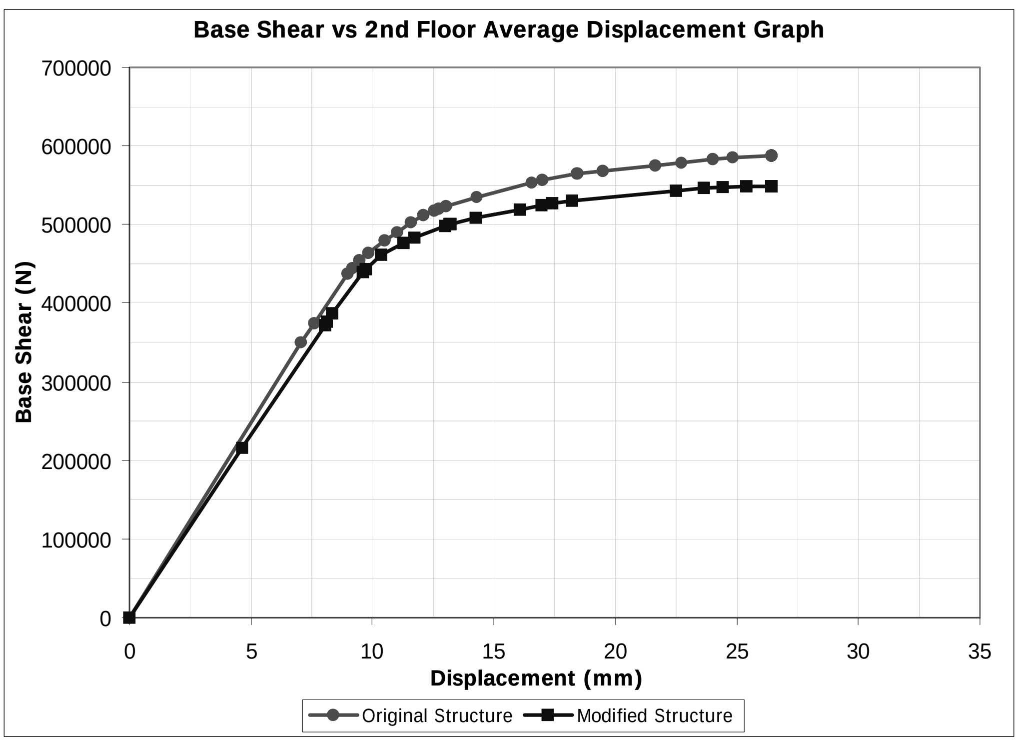

Figure 5.23 (-) X Direction Pushover for Building 1. Removed Member: C0106

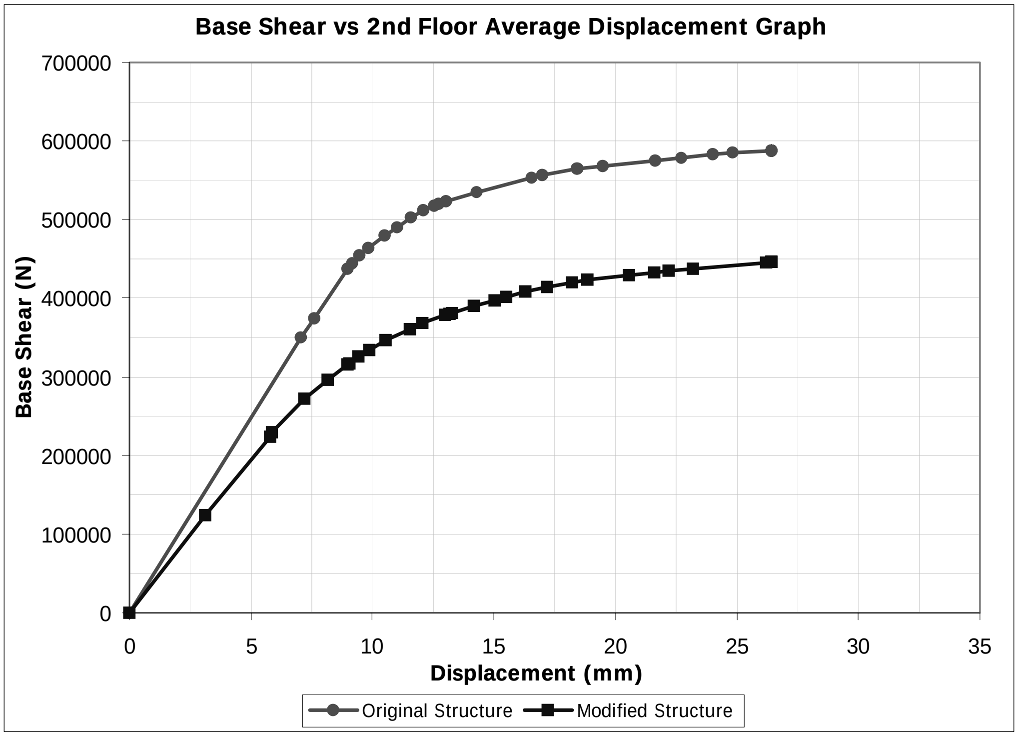

Figure 5.24 (-) X Direction Pushover for Building 1. Removed Member: C0107

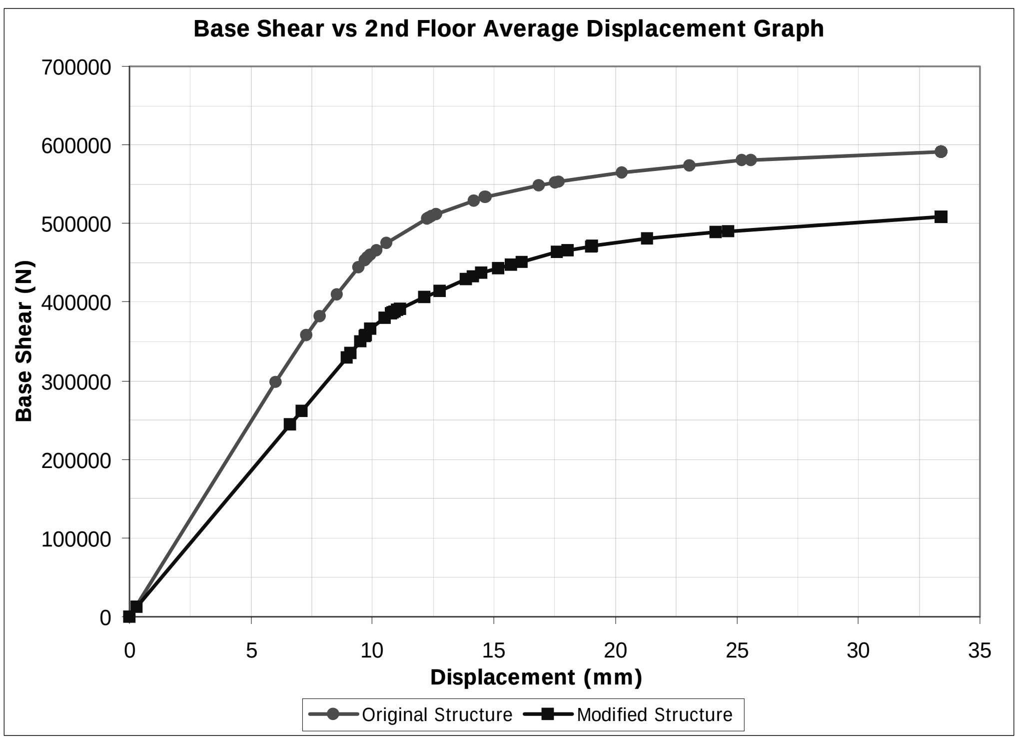

Figure 5.25 (+) X Direction Pushover for Building 1. Removed Member: C0108

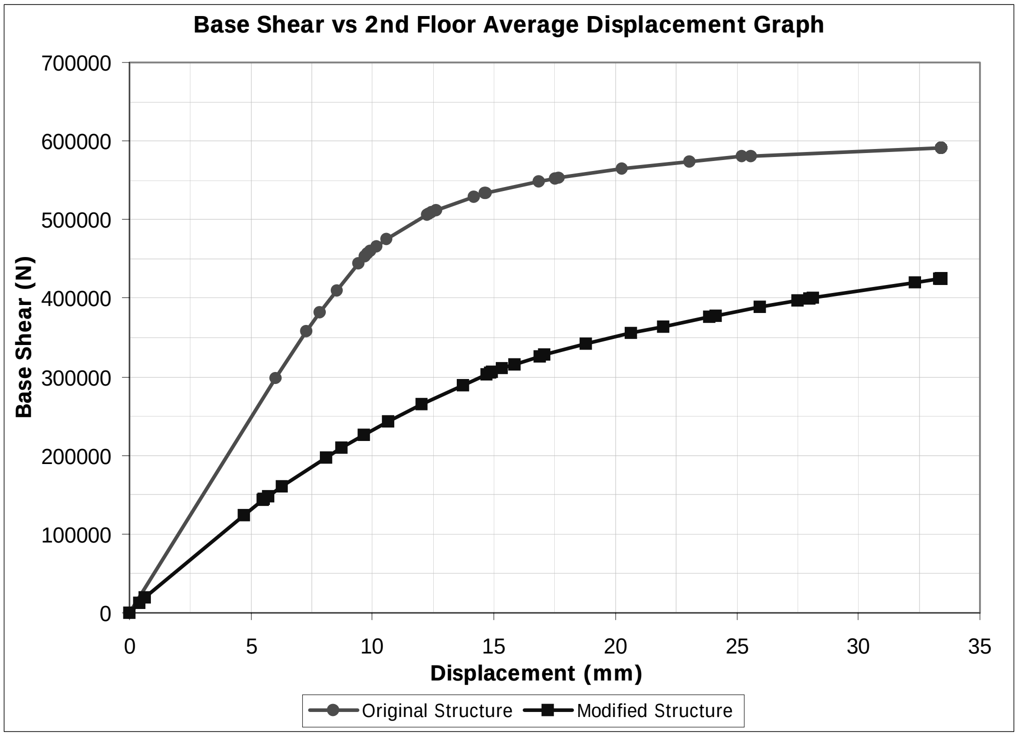

Figure 5.26 (+) X Direction Pushover for Building 1. Removed Member: C0109

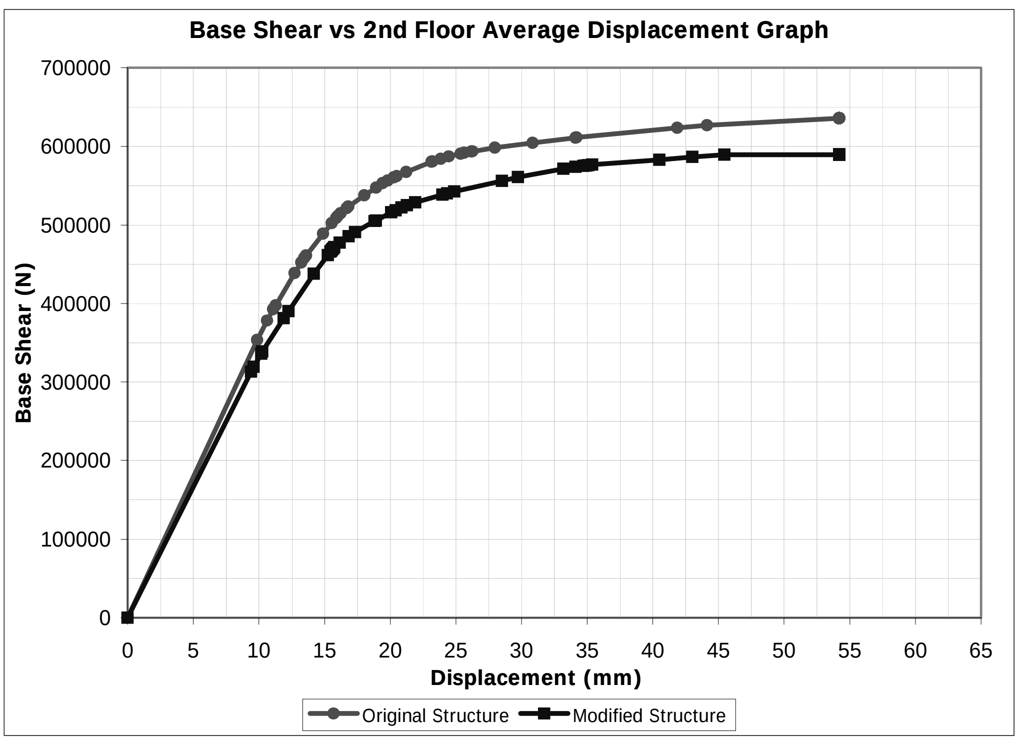

Figure 5.27 (-) Y Direction Pushover for Building 1. Removed Member : C0101

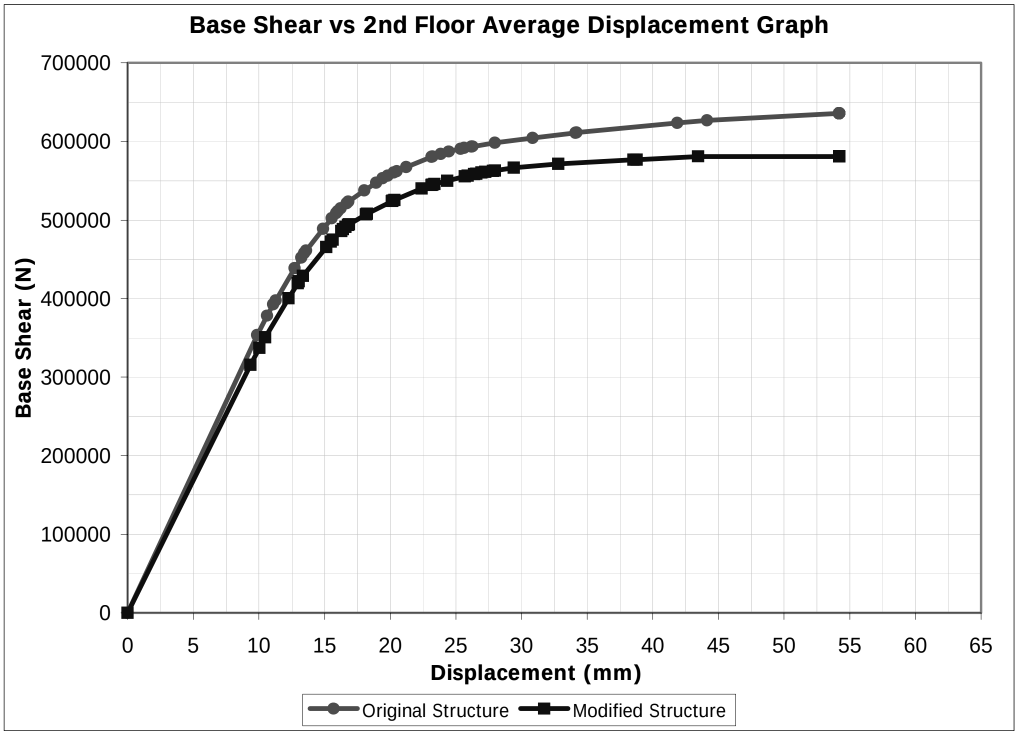

Figure 5.28 (-) Y Direction Pushover for Building 1. Removed Member : C0102

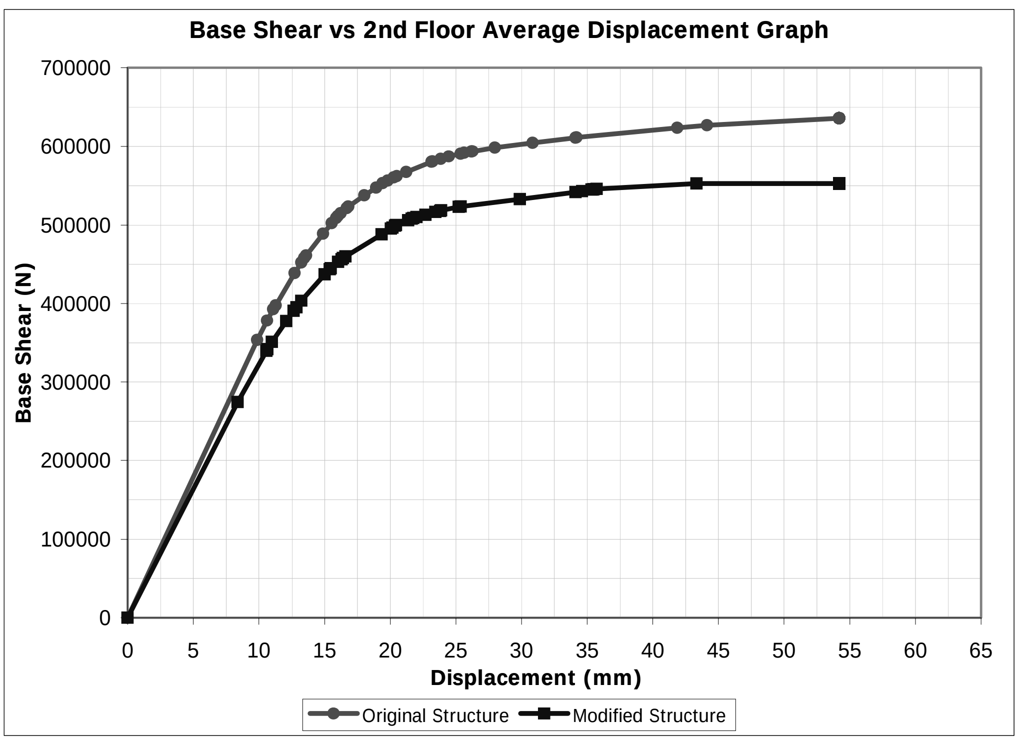

Figure 5.29 (-) Y Direction Pushover for Building 1. Removed Member : C0103

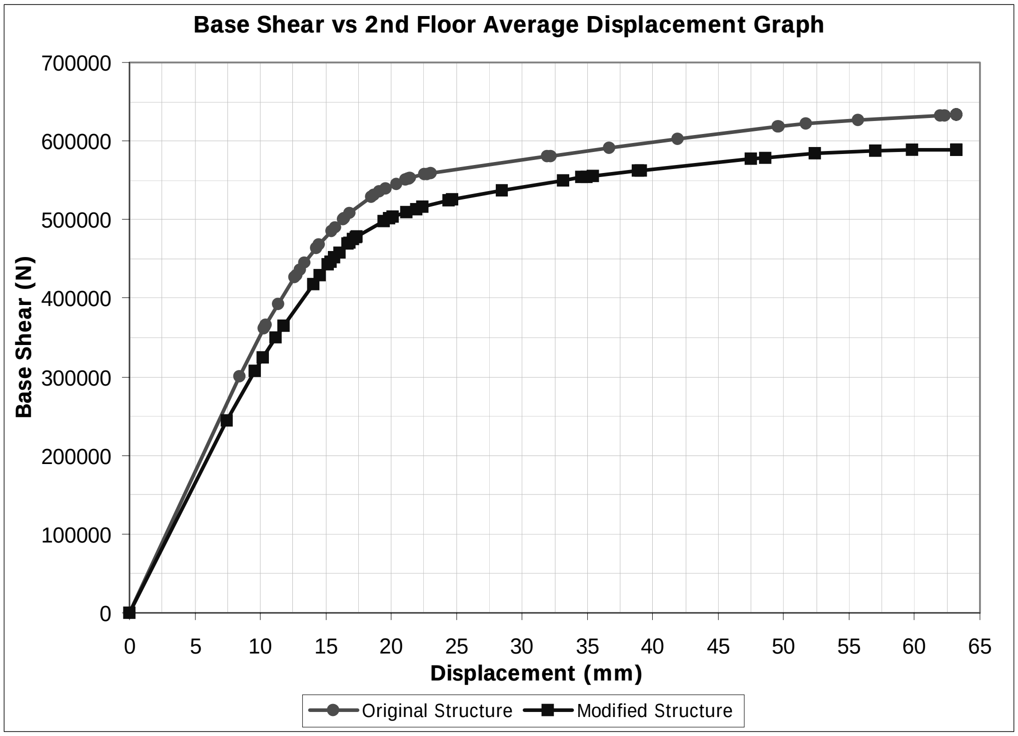

Figure 5.30 (+) Y Direction Pushover for Building 1. Removed Member : C0104

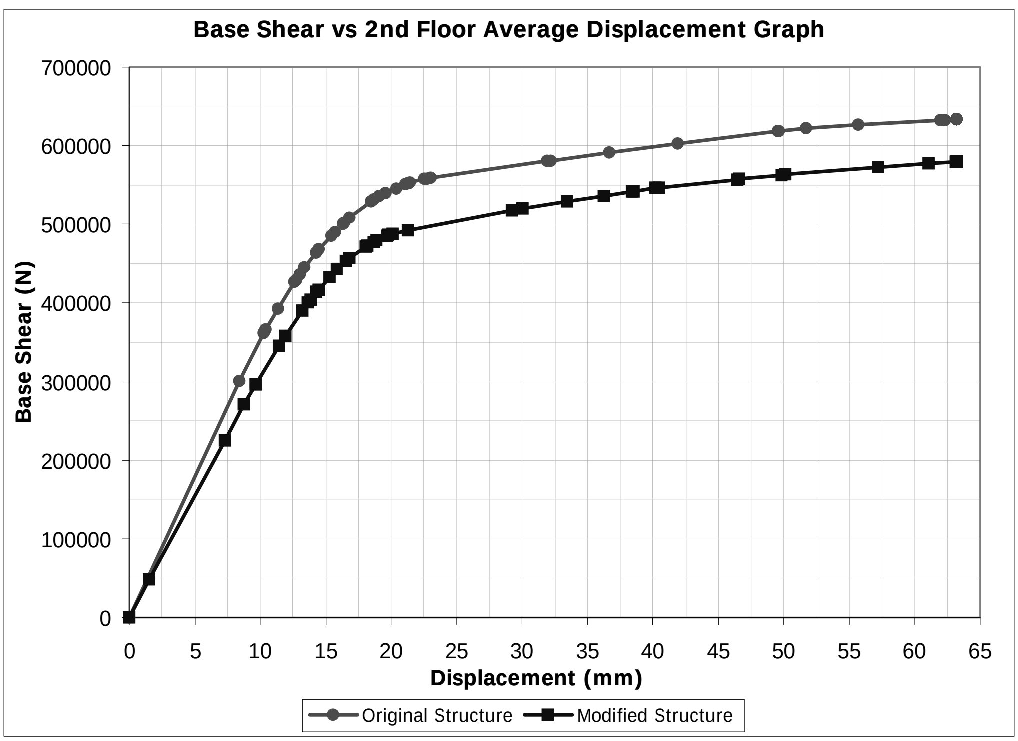

Figure 5.31 (+) Y Direction Pushover for Building 1. Removed Member : C0105

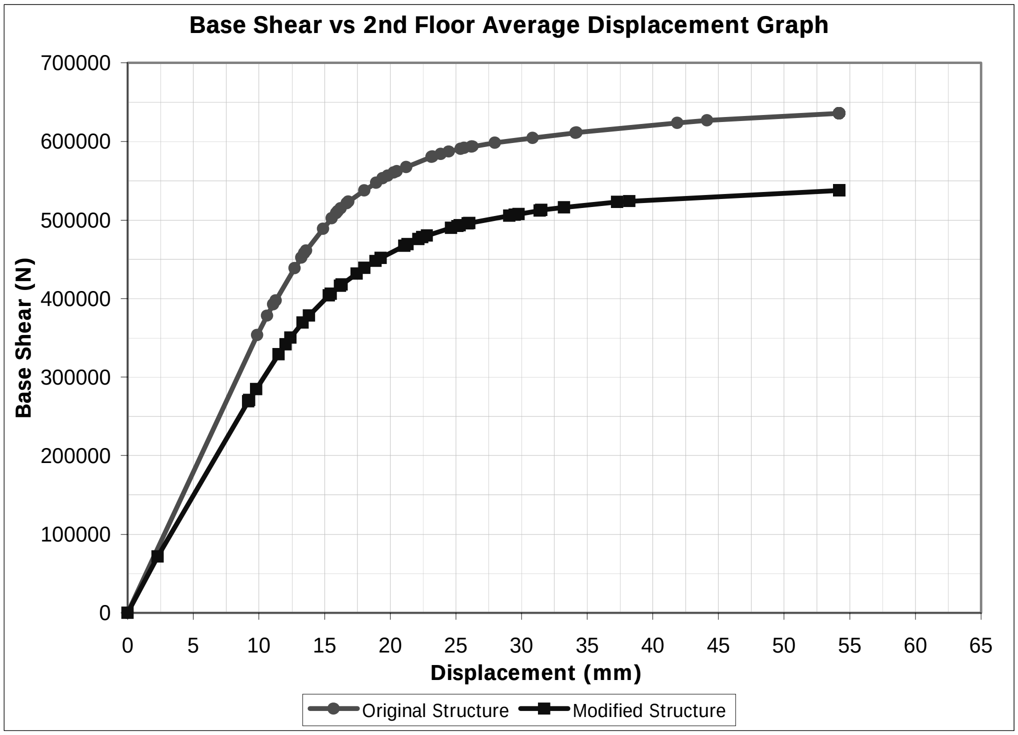

Figure 5.32 (-) Y Direction Pushover for Building 1. Removed Member C0106

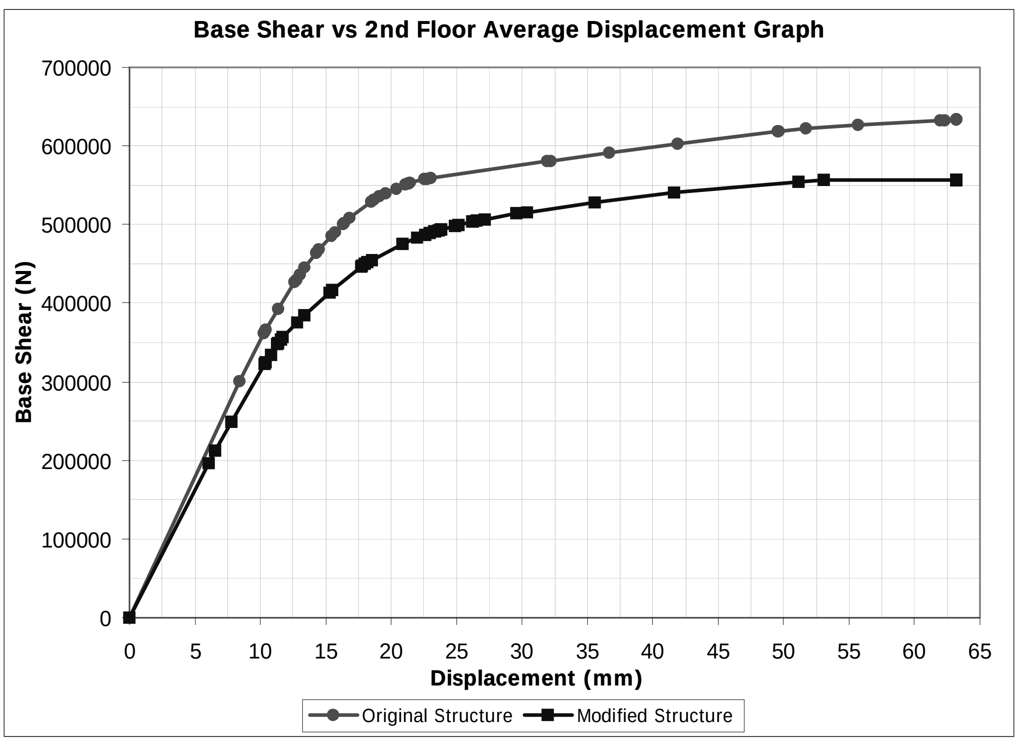

Figure 5.33 (+) Y Direction Pushover for Building 1. Removed Member: C0107

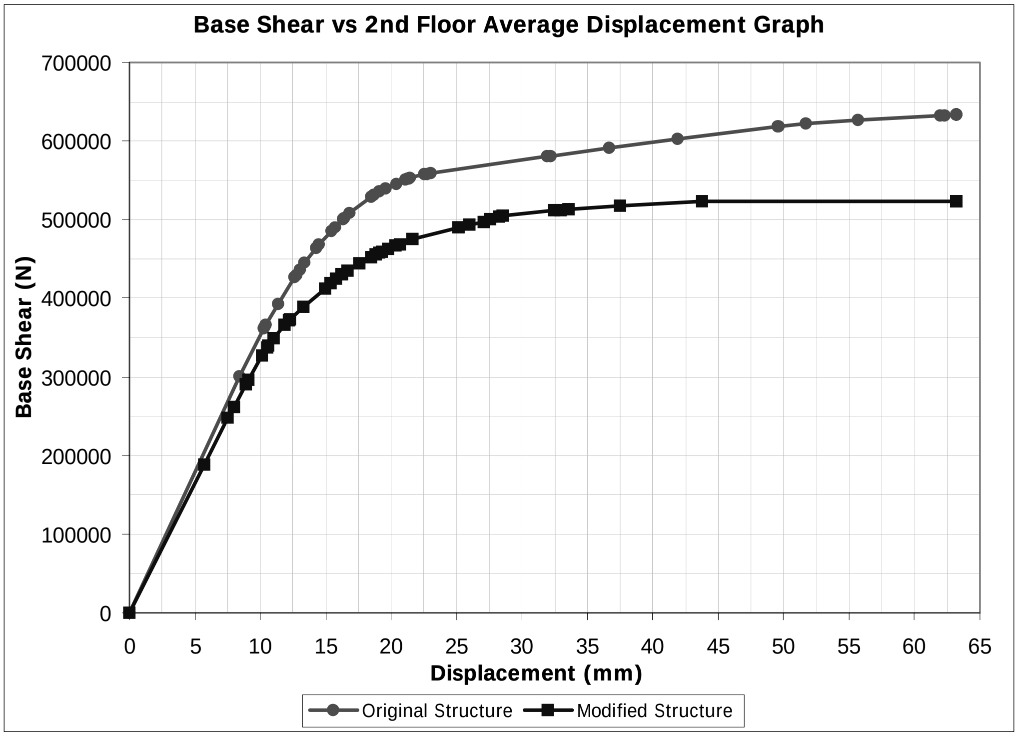

Figure 5.34 (+) Y Direction Pushover for Building 1. Removed Member: C0108

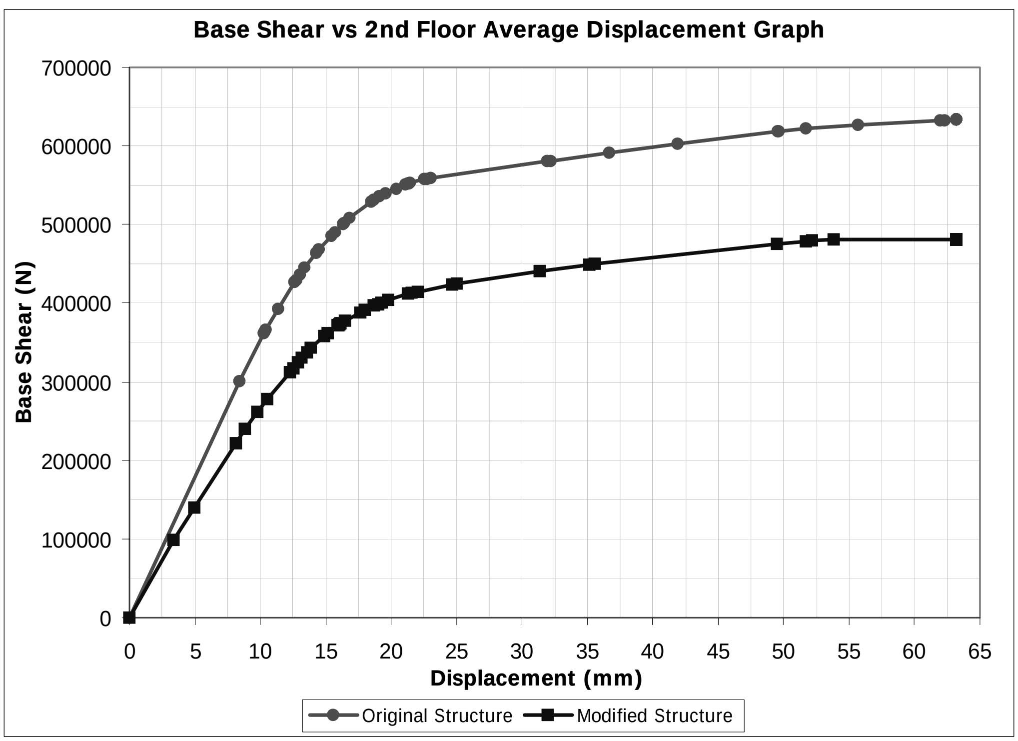

Figure 5.35 (+) Y Direction Pushover for Building 1. Removed Member: C0109

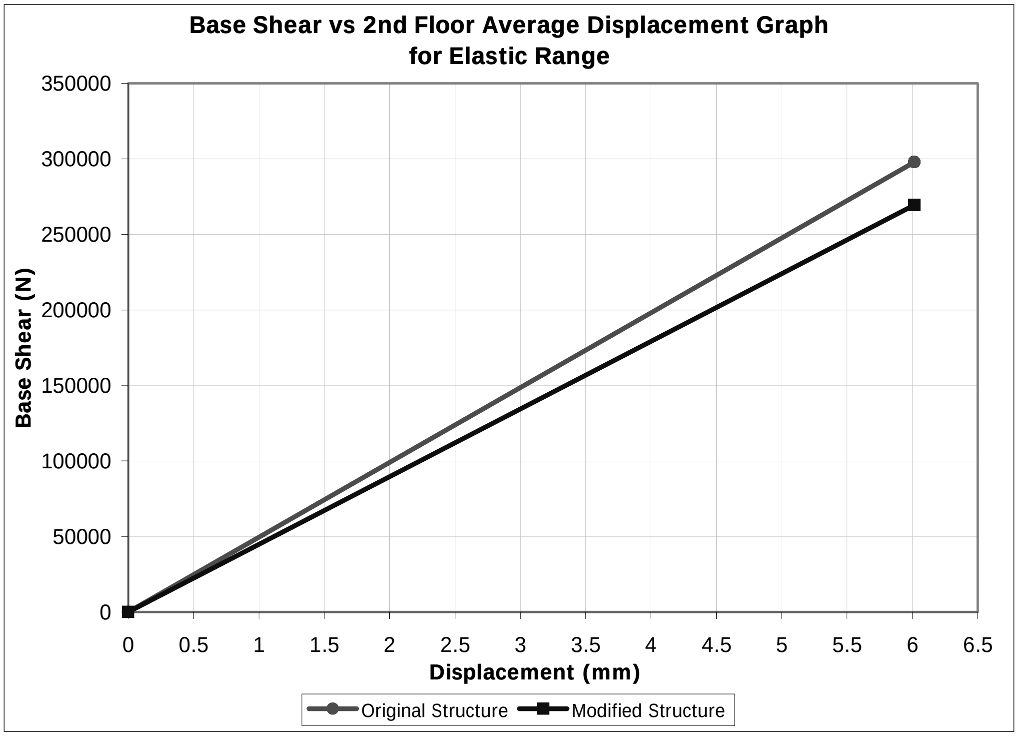

Figure 5.36 (+) X Direction Pushover for Elastic Range. Removed Member: C0101

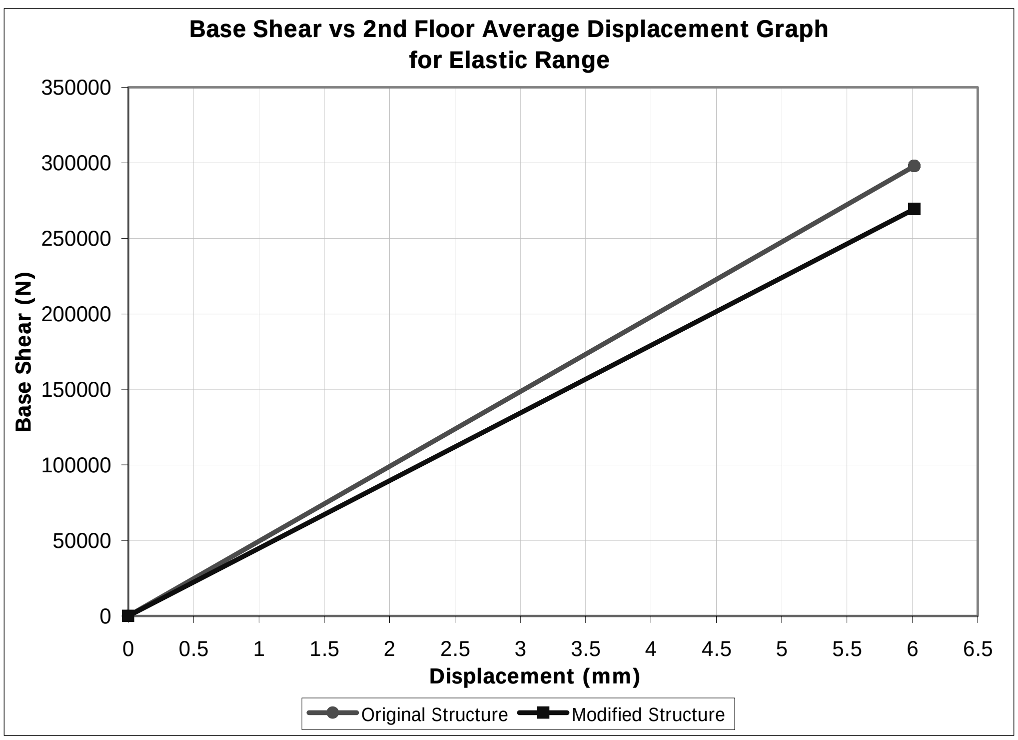

Figure 5.37 (+) Y Direction Pushover for Elastic Range. Removed Member: C0101

Discussion of the Results

After pushover analyses are conducted in both directions, importance factors are determined with the methodology described in section 2.2.3.5. Determined importance factors for all base members are displayed in Table 5.3 for elastic and plastic approaches.

Table 5.3 Importance Factors for Elastic and Plastic Approaches

	Importance Factors			
	Elastic Approach		Plastic Approach	
Member	X Direction (EX)	Y Direction (EY)	X Direction (PX)	Y Direction (PY)
C0101	0.096	0.069	0.021	0.069
C0102	0.073	0.056	0.000	0.066
C0103	0.086	0.086	0.023	0.114
C0104	0.082	0.075	0.106	0.066
C0105	0.085	0.102	0.066	0.098
C0106	0.062	0.127	0.056	0.163
C0107	0.202	0.092	0.254	0.113
C0108	0.180	0.075	0.172	0.137
C0109	0.340	0.187	0.386	0.239

The ratio of importance factors obtained by plastic approach to importance factors obtained by elastic approach shows difference in two evaluation methods. The results are presented in Table 5.4.

Table 5.4 Importance Factors Comparison for Elastic and Plastic Approaches

Importance Factor Comparison		
Member	X Direction	Y Direction
C0101	21.5%	100.2%
C0102	-0.2%	117.5%
C0103	26.5%	133.2%
C0104	129.8%	89.1%
C0105	77.8%	96.0%
C0106	89.8%	128.6%
C0107	125.3%	123.0%
C0108	95.7%	182.2%
C0109	113.6%	127.9%

Differences in the importance factors for elastic and plastic approaches shown in Table 5.4 indicate that the plastic and elastic approaches are not substitute of each other.

The building is frame type structure and show ductile behavior in both directions. There is no sudden drop in the pushover curves, which indicates that none of the columns failed due to shear. The mechanism forms by utilization of hinges at the ends of columns.

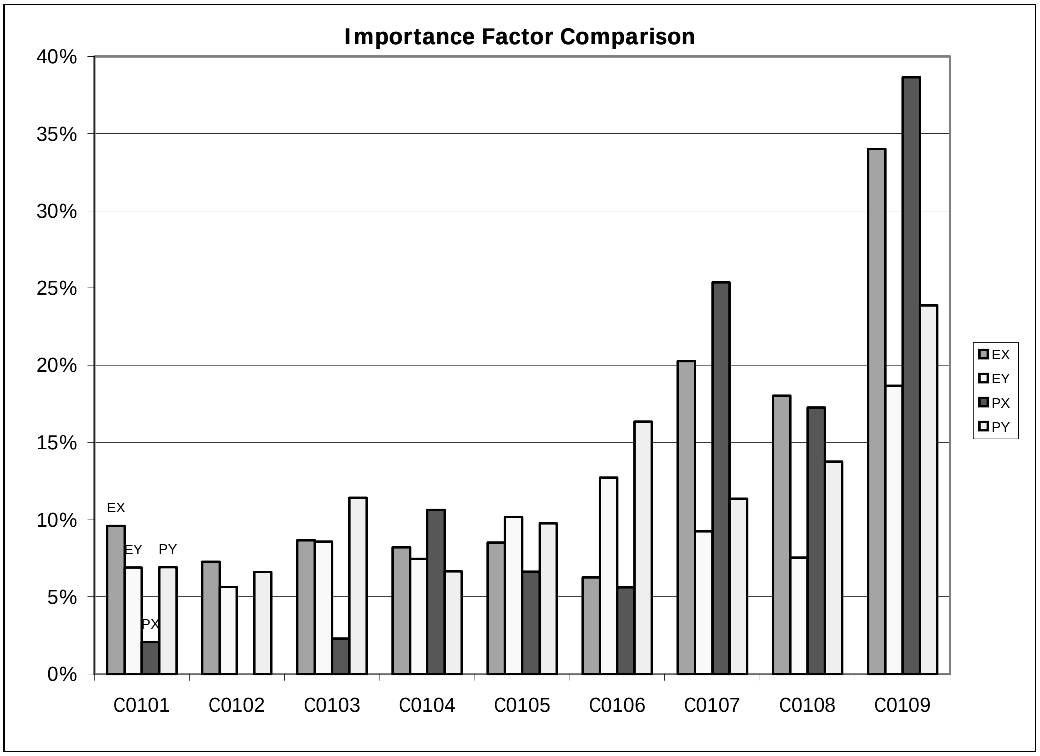

Figure 5.38 Member Importance Factors for Building 1

Figure 5.38 display the distribution of importance factors along members in X and Y directions for elastic and plastic approaches. The comparison of X direction importance factors shows reasonably close values for columns between C0101 to C0103, however the columns from C0107 to C0109 have large differences. The first three columns are located at the narrow side of the building, which significantly moves the stiffness center location closer to mass center reducing the eccentricity and causing a translational mode shape. The Y direction plastic importance factors (PY) are larger than the elastic counterparts (EY) in general. This difference is mainly caused by larger ratio of capacity curve areas at the non-linear range compared to the ratio of curve areas in the linear range. In the graph in both directions high importance of column C0106, C0107 C0108 and C0109 is observed.

These columns are located under floor with high irregularity in plan and near the overhang. When these members are removed form the structure, plastic hinges at the ends of the beams take place at early stages of the analyses and distribution of loads change considerably. And column C0107 and C01019 are good examples that show the variation of importance by direction. These columns have low contribution in Y direction with respect to X direction.

Figures 5.39 and 5.40 display the distribution of importance factors on plan of the building in X and Y directions, respectively. The diameters of the circles are proportional with the importance assigned to each member.

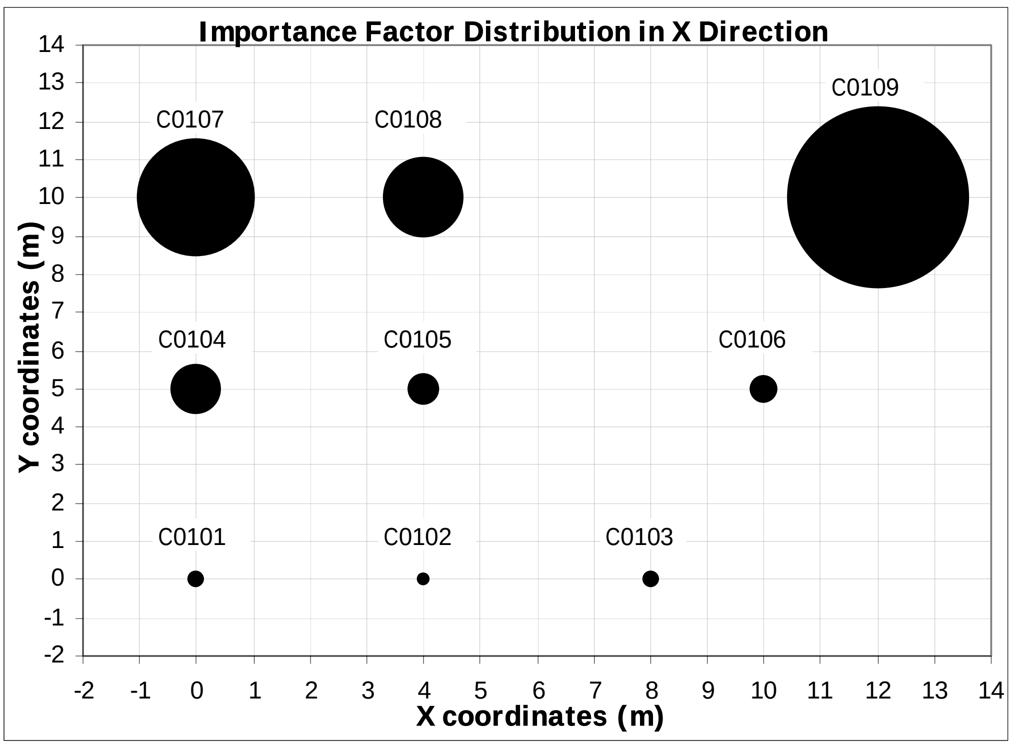

Figure 5.39 Importance Factor Distribution in X Direction for Building 1

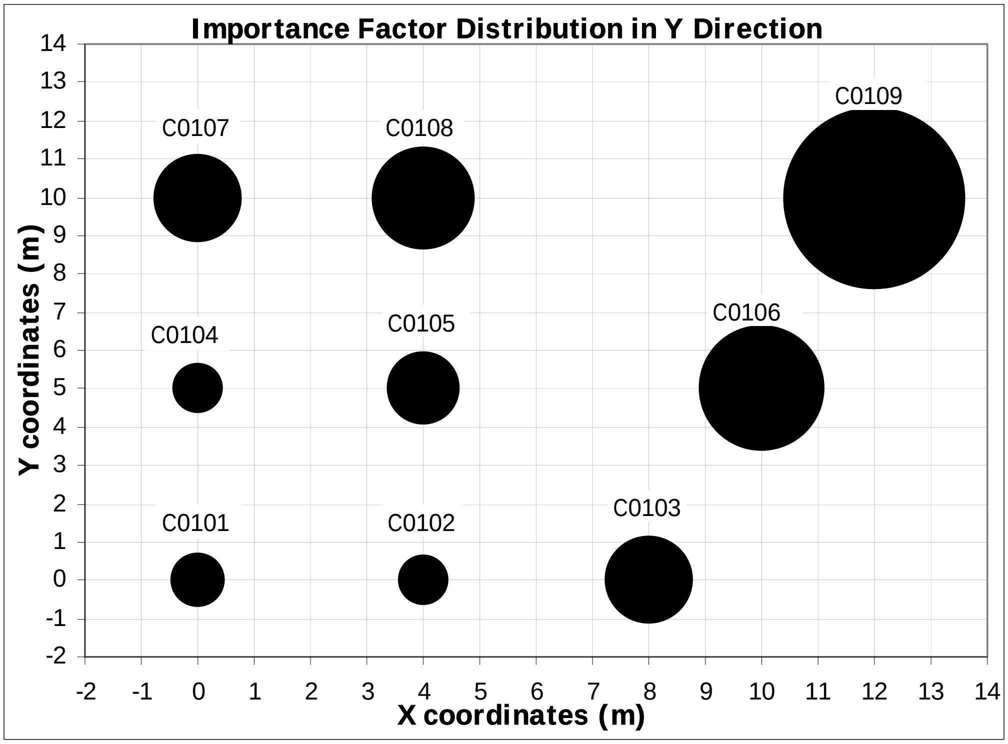

Figure 5.40 Importance Factor Distribution in Y Direction for Building 1

5.3.2 BUILDING 2

Modified version of Building 1, for which the details are presented in section 5.3.1, is evaluated in this section. Columns C0101, C0102 are removed and shear wall with section type SW01 is placed instead of them. The details of the shear wall are displayed in Figure 5.41

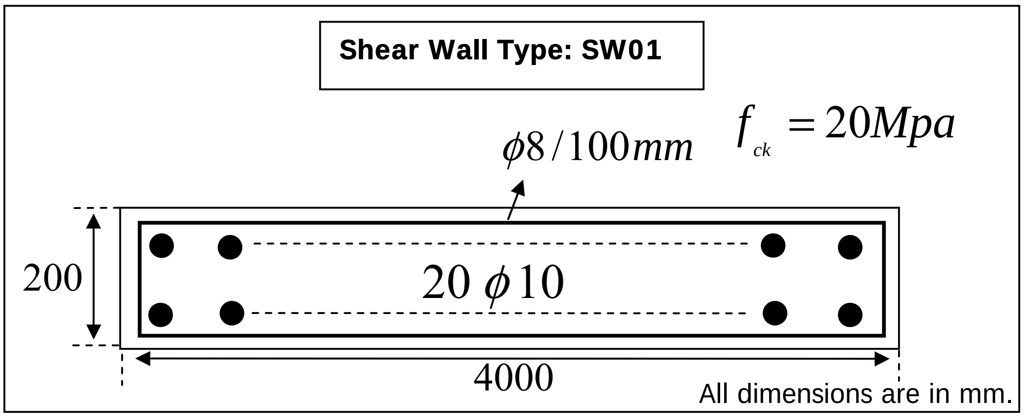

Figure 5.41 Details of Shear Wall Type SW01

This model is constructed to show the affect of shear wall to the base shear capacity and behavior of the building. The X and Y dominant mode shapes used in the analysis are displayed in Figures 5.42 and 5.43, respectively. The pushover curves obtained in X and Y directions are presented in figures 5.44 to 5.59.

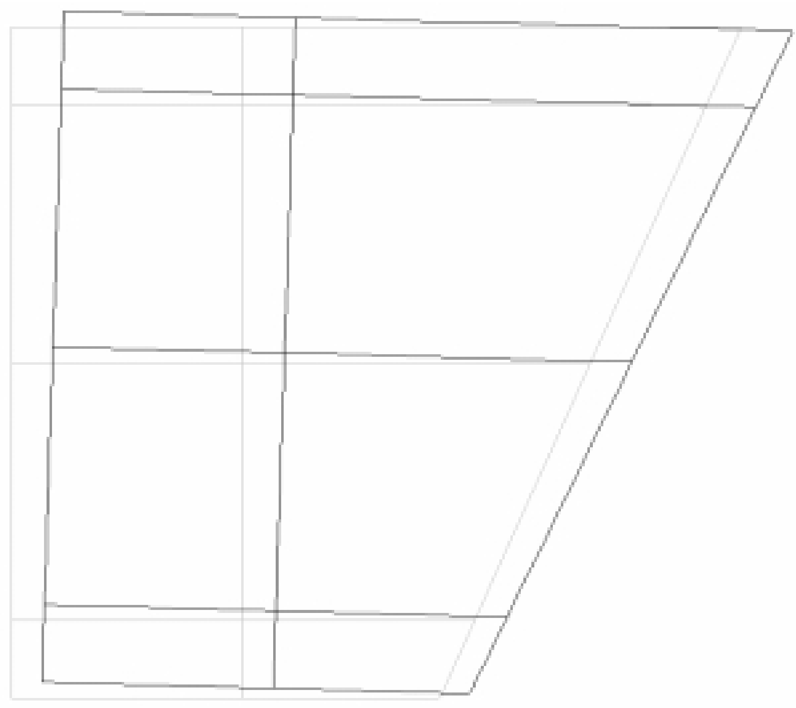

Figure 5.42 Mode Shape in X Dominant Direction for Building 1

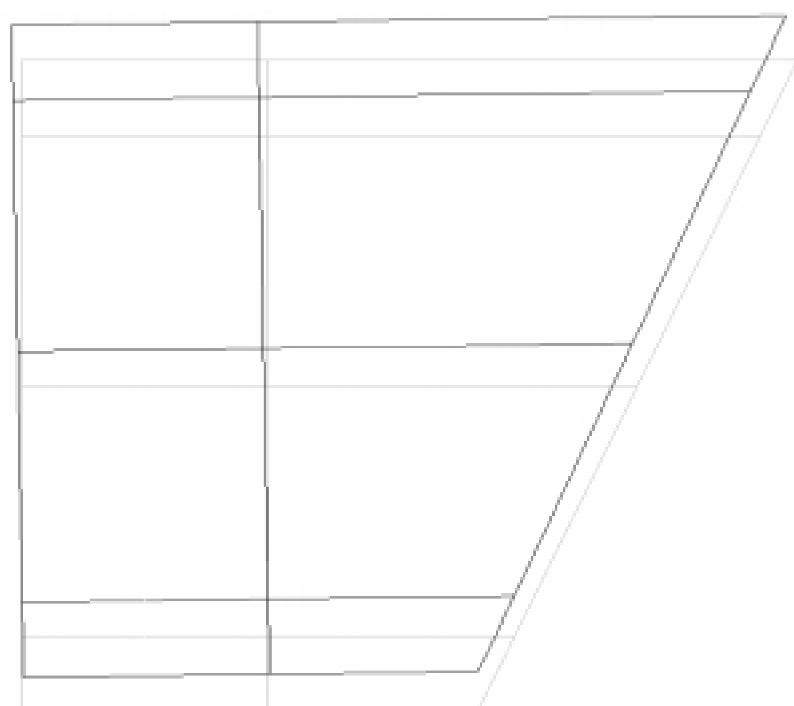

Figure 5.43 Mode Shape in Y Dominant Direction for Building 2

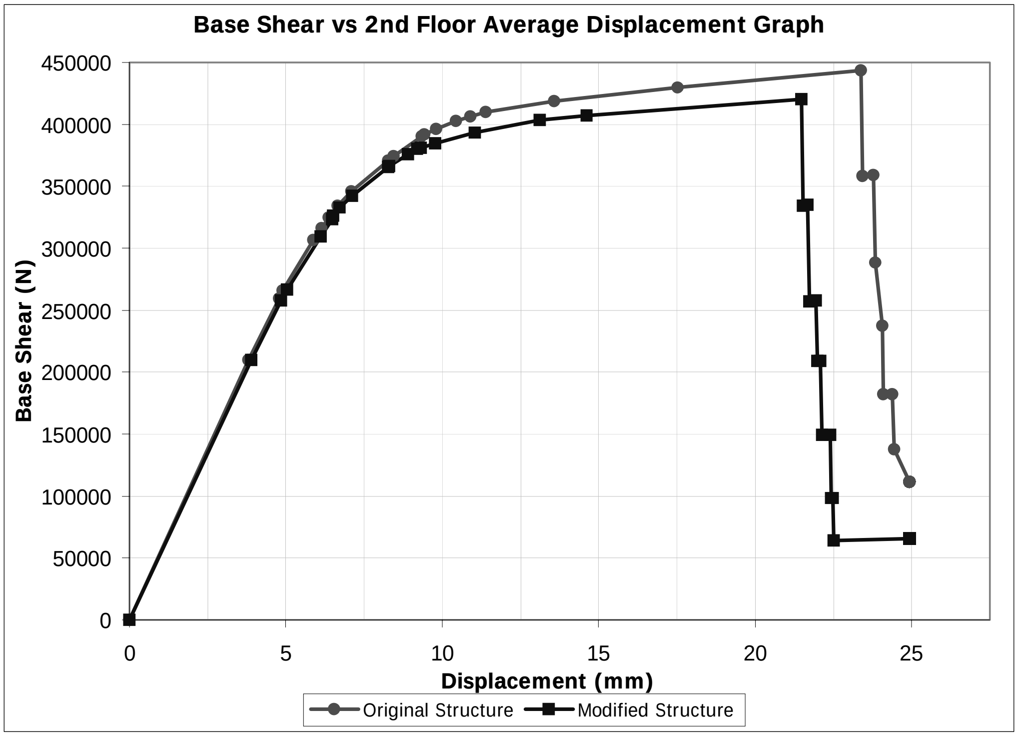

Figure 5.44 (+) X Direction Pushover for Building 2. Removed Member: C0103

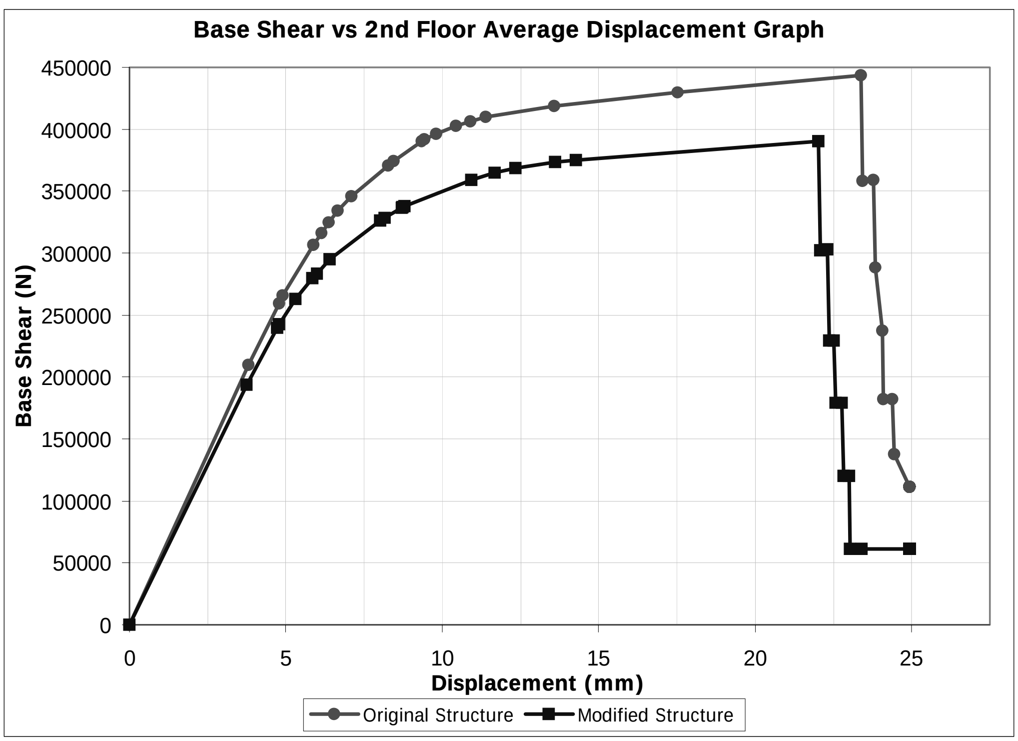

Figure 5.45 (+) X Direction Pushover for Building 2. Removed Member: C0104

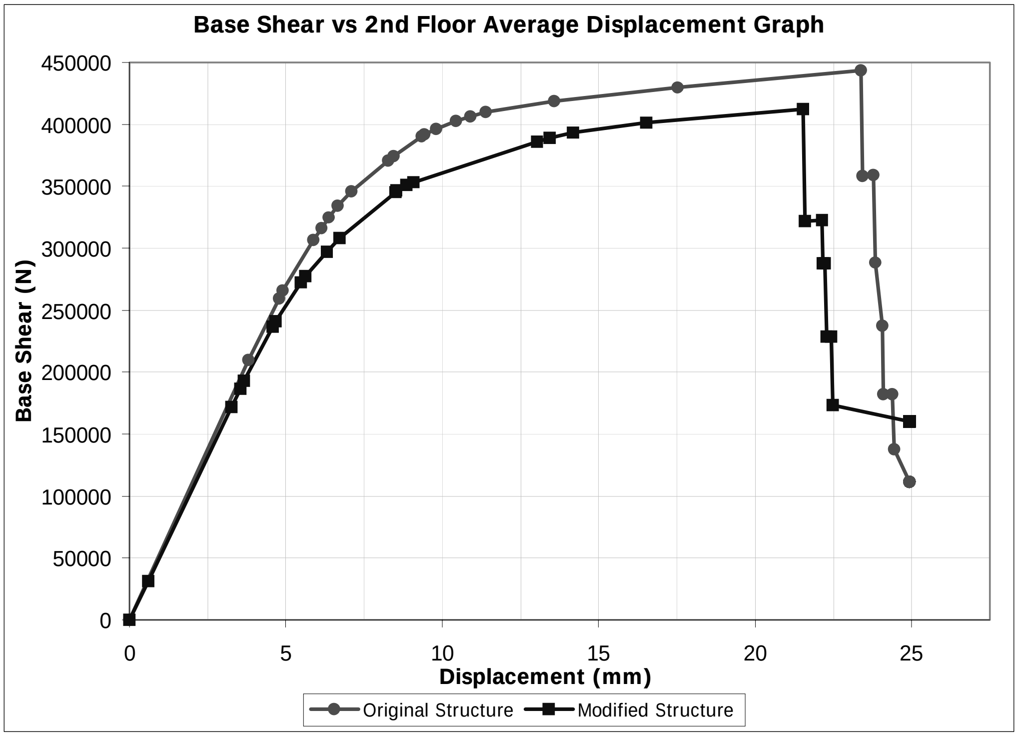

Figure 5.46 (+) X Direction Pushover for Building 2. Removed Member: C0105

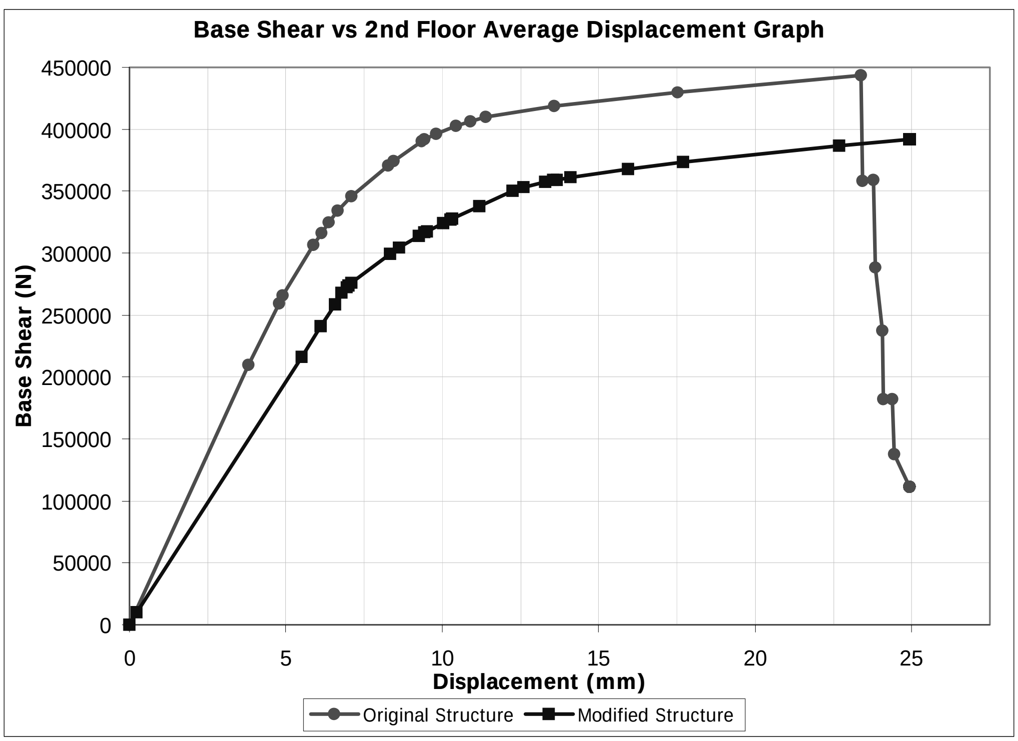

Figure 5.47 (+) X Direction Pushover for Building 2. Removed Member: C0106

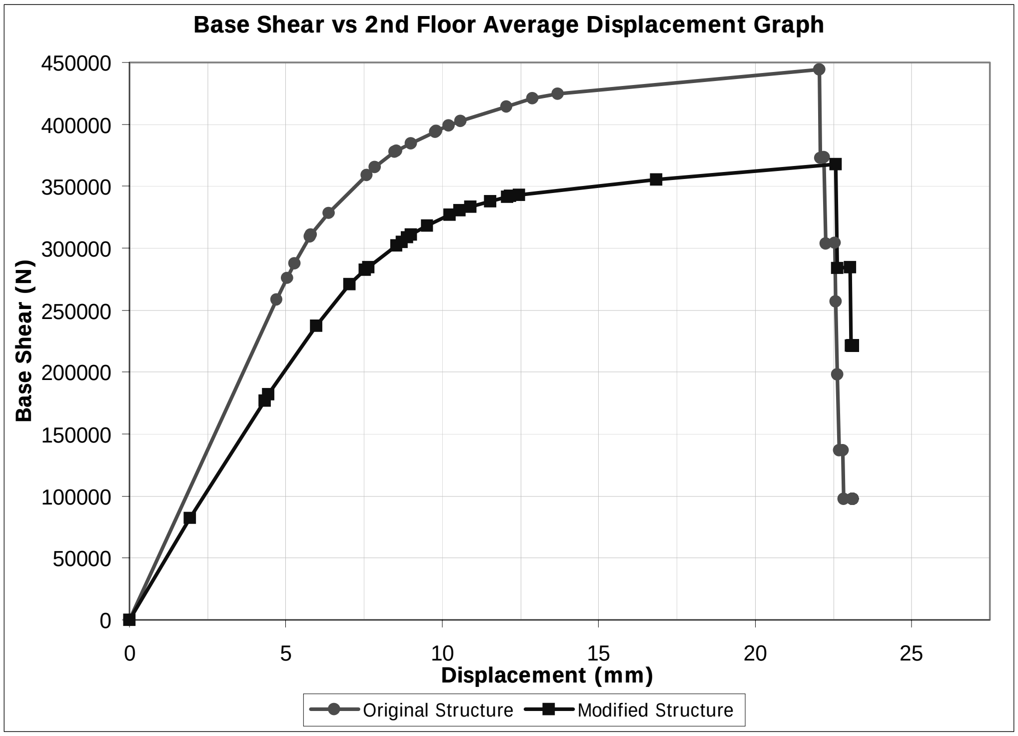

Figure 5.48 (+) X Direction Pushover for Building 2. Removed Member: C0107

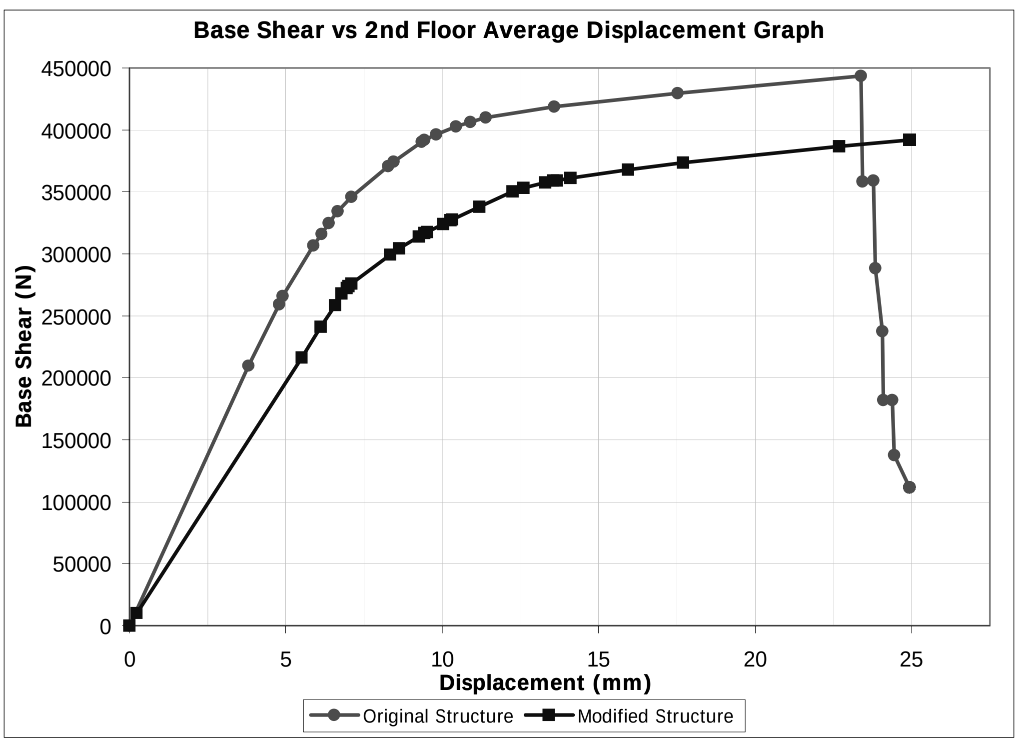

Figure 5.49 (-) X Direction Pushover for Building 2. Removed Member: C0108

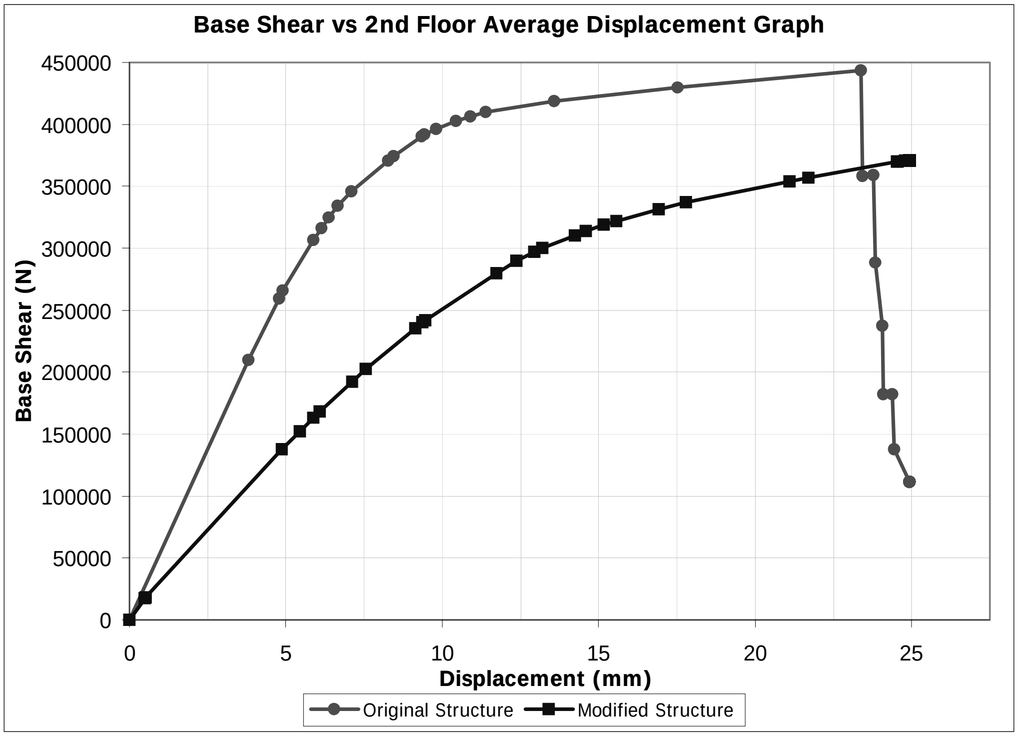

Figure 5.50 (+) X Direction Pushover for Building 2. Removed Member: C0109

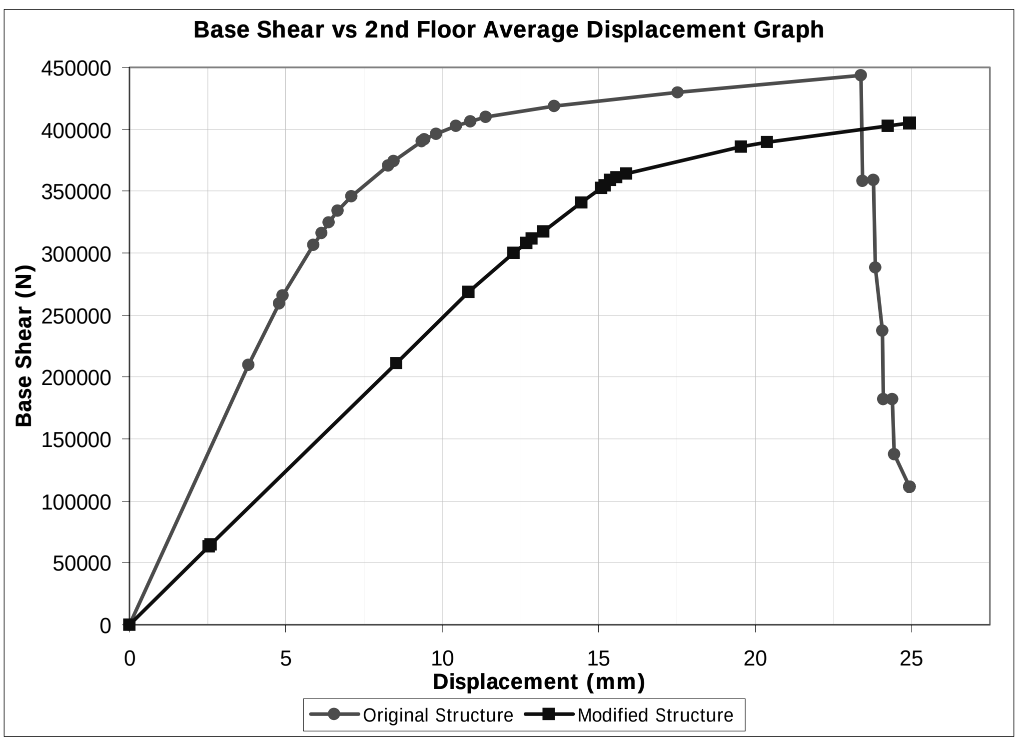

Figure 5.51 (+) X Direction Pushover for Building 2. Removed Member: SW0101

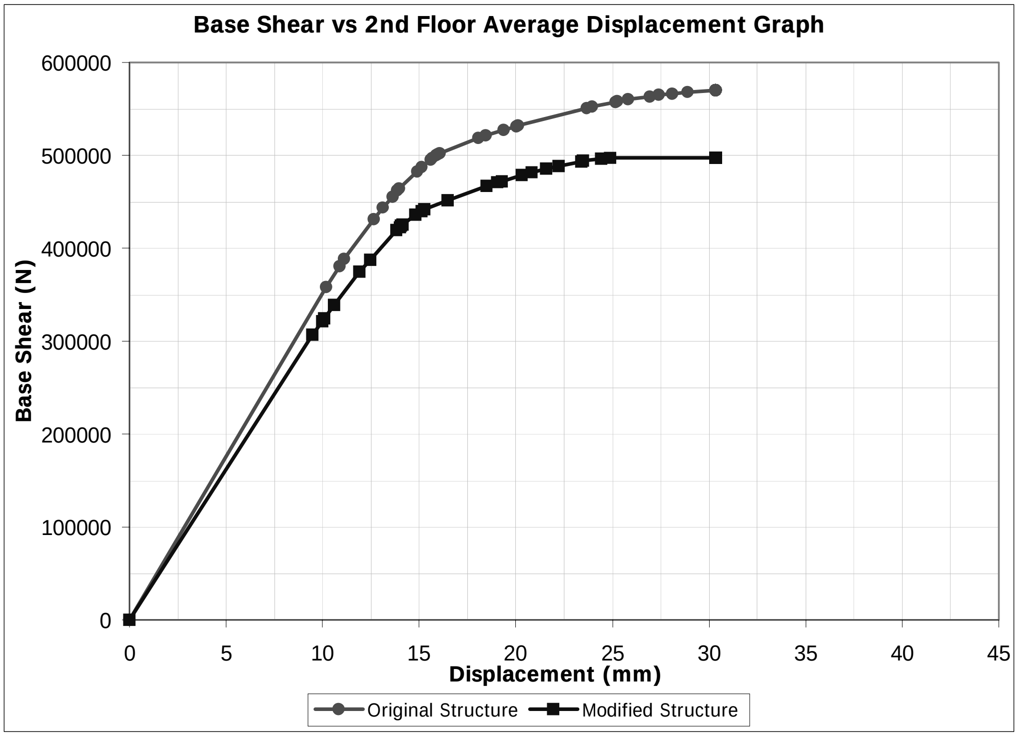

Figure 5.52 (-) Y Direction Pushover for Building 2. Removed Member: C0103

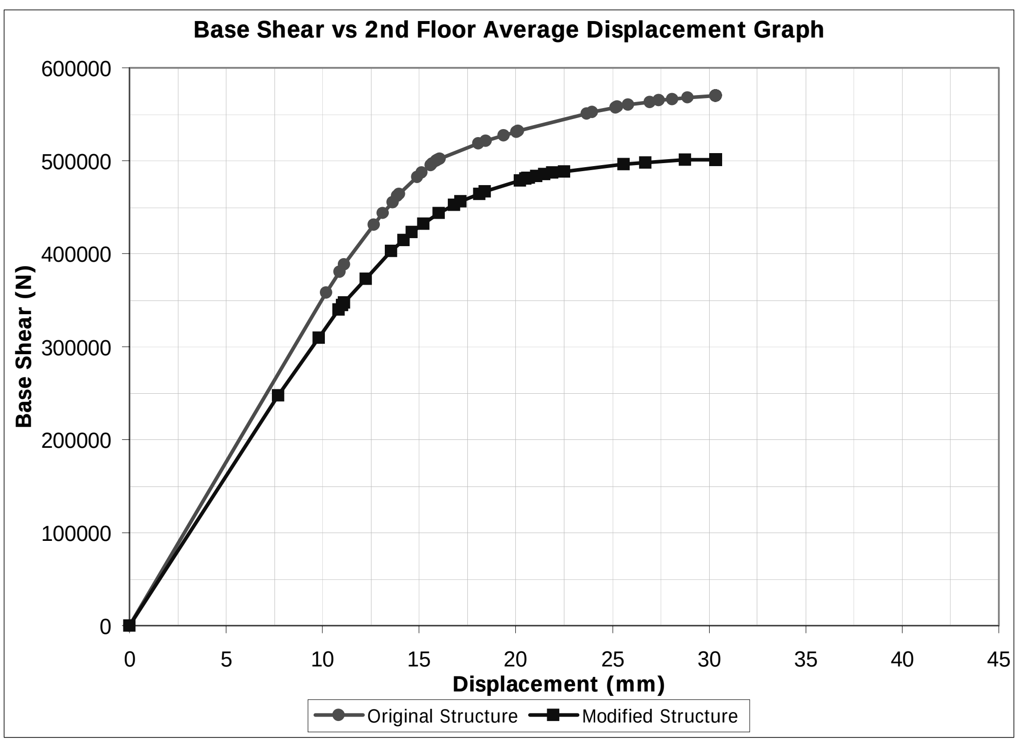

Figure 5.53 (-) Y Direction Pushover for Building 2. Removed Member: C0104

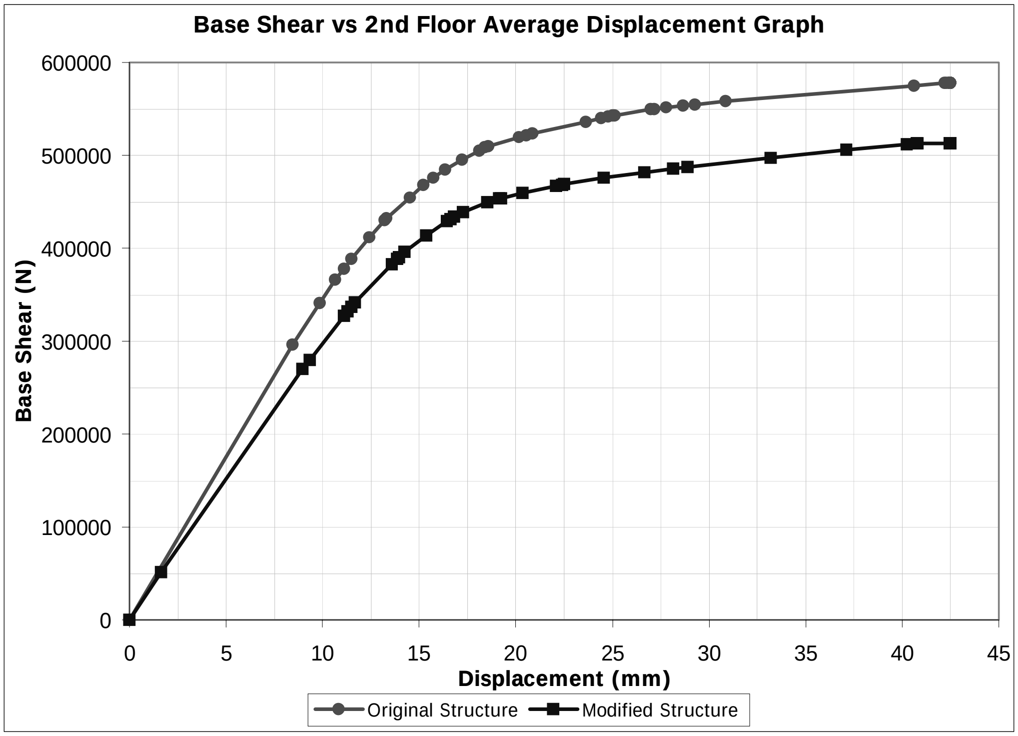

Figure 5.54 (+) Y Direction Pushover for Building 2. Removed Member: C0105

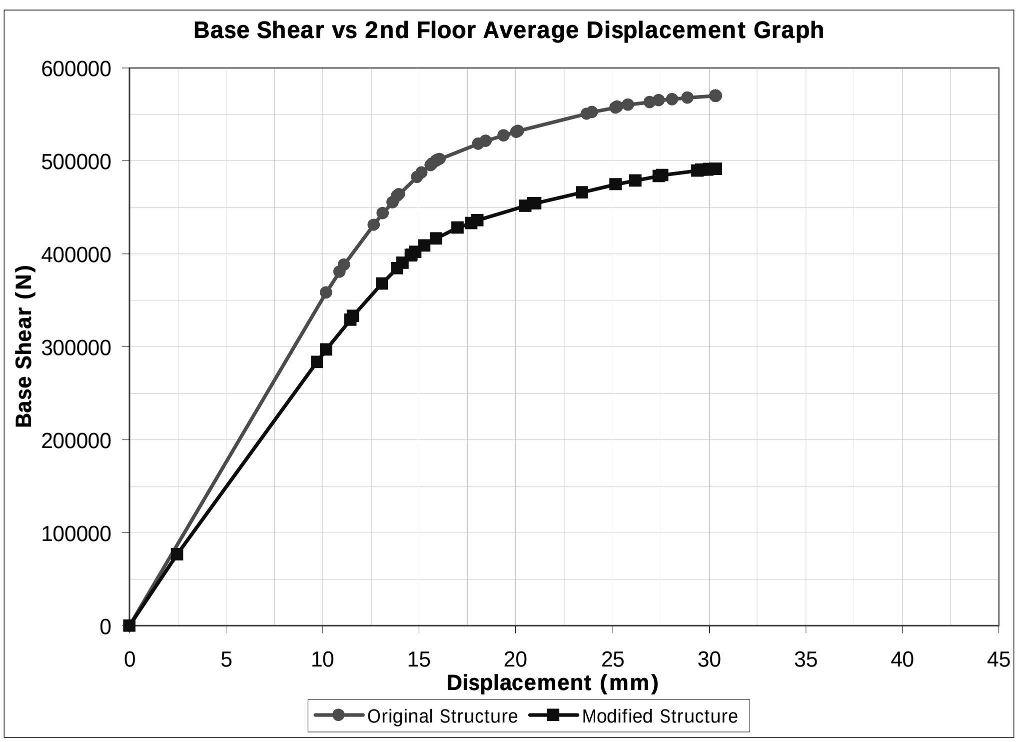

Figure 5.55 (-) Y Direction Pushover for Building 2. Removed Member: C0106

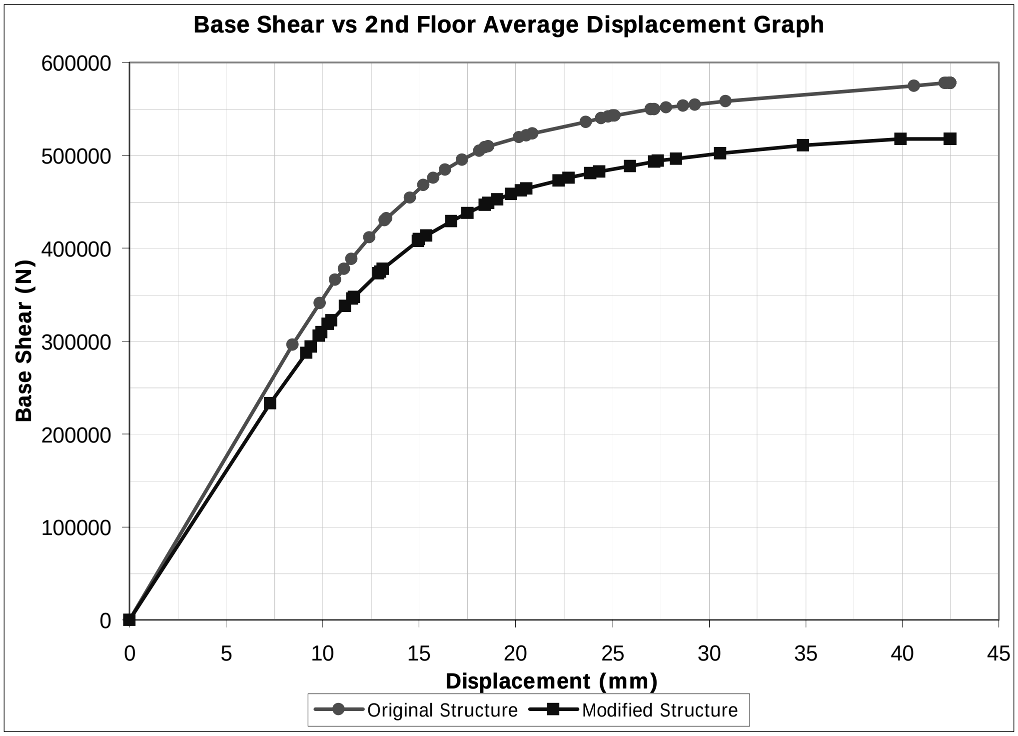

Figure 5.56 (+) Y Direction Pushover for Building 2. Removed Member: C0107

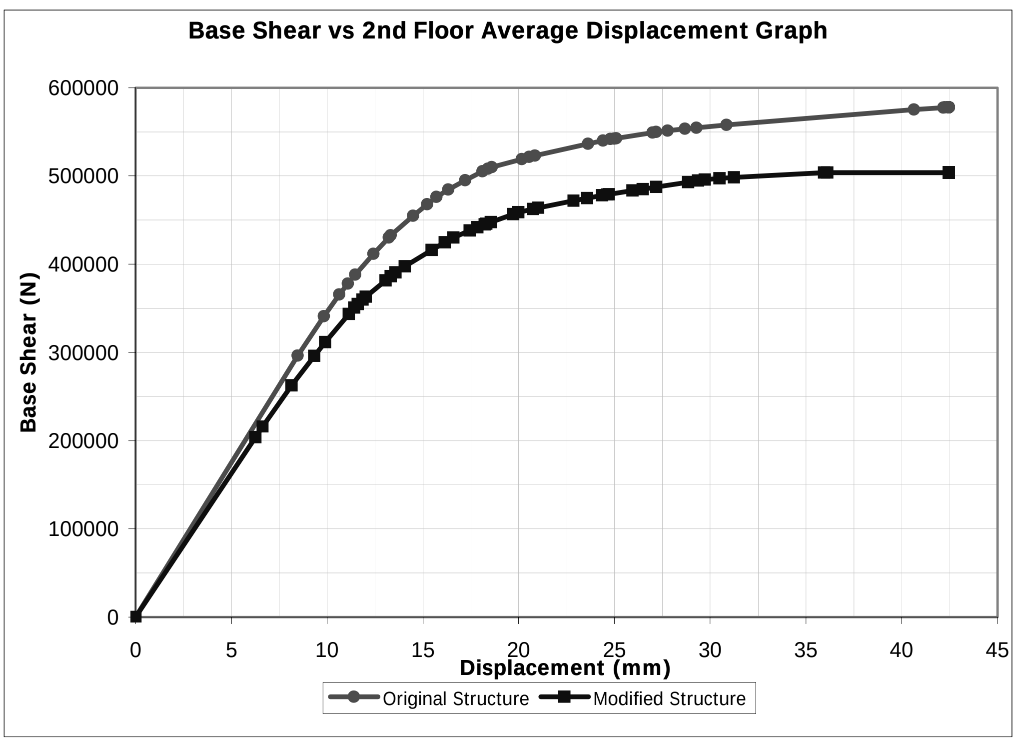

Figure 5.57 (+) Y Direction Pushover for Building 2. Removed Member: C0108

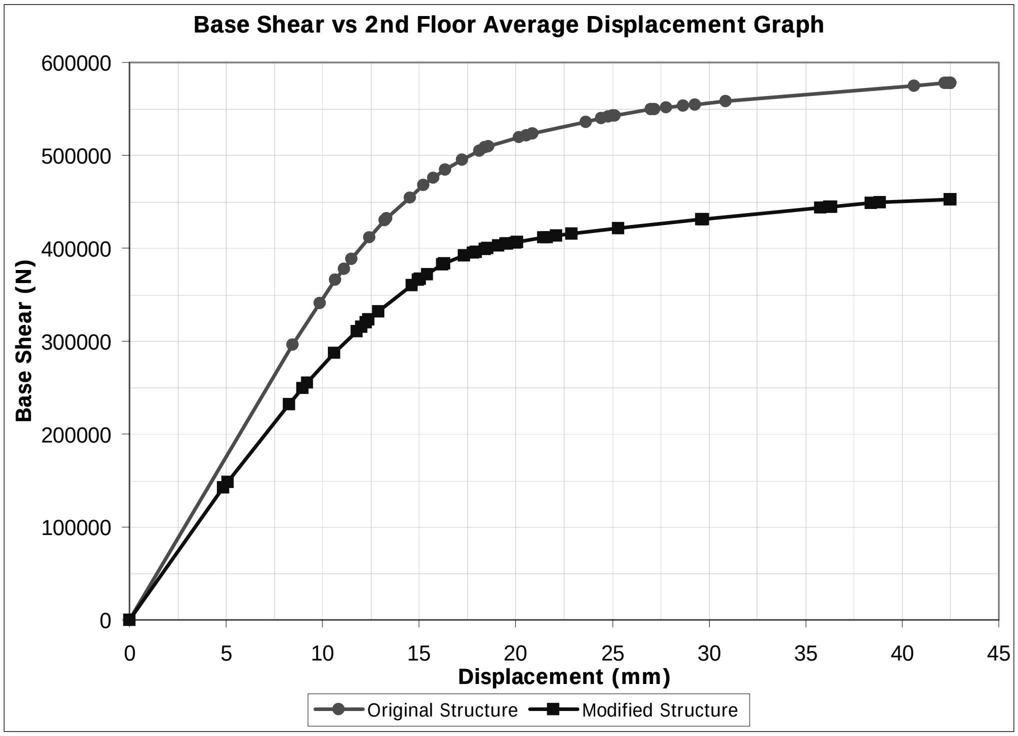

Figure 5.58 (+) Y Direction Pushover for Building 2. Removed Member: C0109

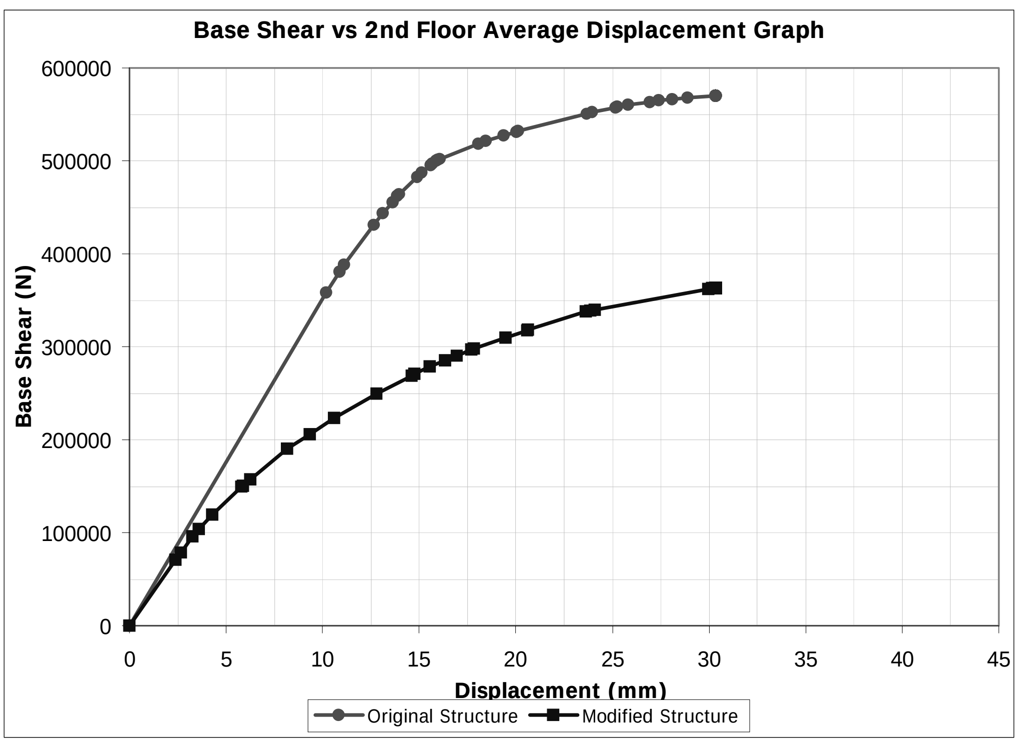

Figure 5.59 (-) Y Direction Pushover for Building 2. Removed Member: SW0101

Discussion of the Results

After pushover analyses are conducted in both directions, importance factors are determined with the methodology described in section 2.2.3.5. Determined importance factors for all base members are displayed in Table 5.5 for elastic and plastic approaches.

Table 5.5 Importance Factors for Elastic and Plastic Approaches

	Importance Factors			
	Elastic Approach		Plastic Approach	
Member	**X Direction (EX)**	**Y Direction (EY)**	**X Direction (PX)**	**Y Direction (PY)**
C0103	0.020	0.080	0.121	0.102
C0104	0.066	0.088	0.167	0.107
C0105	0.042	0.108	0.117	0.119
C0106	0.074	0.119	0.065	0.156
C0107	0.228	0.086	0.174	0.104
C0108	0.193	0.073	0.130	0.110
C0109	0.358	0.162	0.263	0.215
SW0101	0.547	0.153	0.225	0.386

The ratio of importance factors obtained by plastic approach to importance factors obtained by elastic approach shows difference in two evaluation methods. The results are presented in Table 5.6.

Table 5.6 Importance Factor Comparison for Elastic and Plastic Approaches

Importance Factor Comparison		
Member	**X Direction**	**Y Direction**
C0103	608%	127%
C0104	253%	122%
C0105	278%	110%
C0106	88%	131%
C0107	77%	121%
C0108	67%	151%
C0109	74%	133%
SW0101	41%	252%

Discrepancy in the results shown in table 5.6 indicates that the plastic and elastic approaches are not substitute of each other.

Figure 5.60 display the distribution of importance factors along members in X and Y directions for elastic and plastic approaches. The comparison of X direction importance factors shows reasonably close importance values, whereas in Y direction, importance of members increases through the overhang.

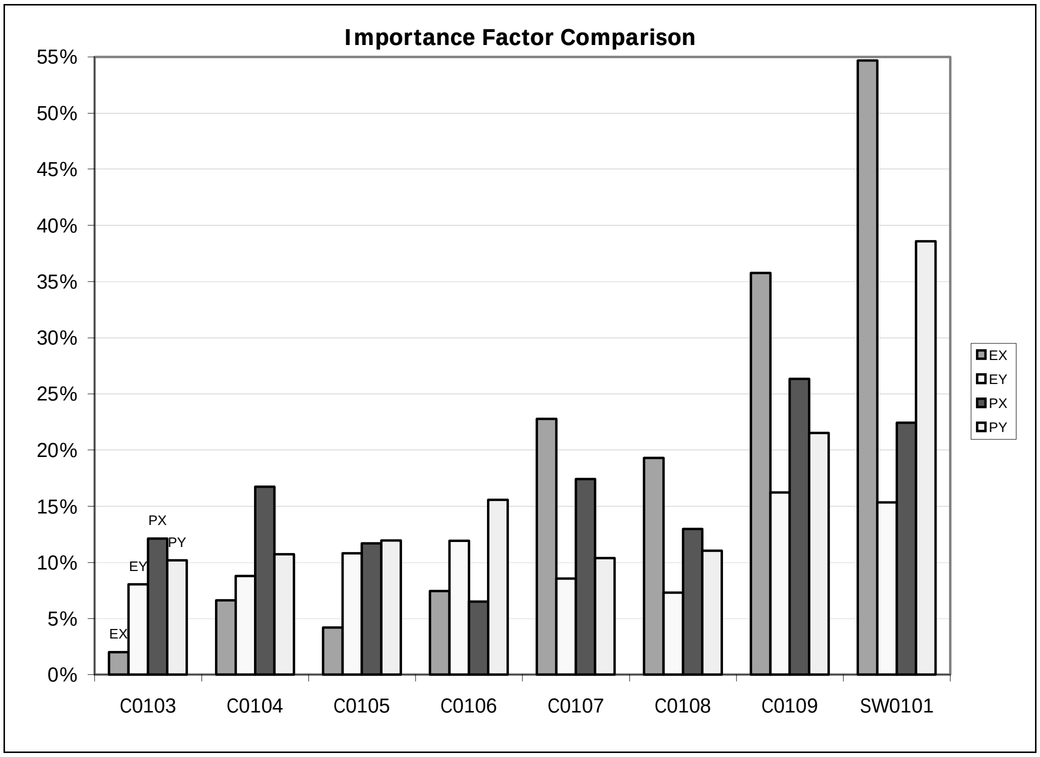

Figure 5.60 Member Importance Factors for Building 2

As observed form pushover curves, building shows brittle behavior in X direction and ductile behavior in Y direction. Placement of shear wall introduces torsion, as seen in X direction dominant mode shape. The building rotates approximately about shear wall location. Due to this behavior, structure fails in torsion prior to distribution of plastic hinges. When shear wall is removed from the structure, stiffness of the building reduces considerably and building show ductile behavior. For this case failure takes place after the maximum displacement of the original building. For elastic approach, relatively low importance of column C0103 in X direction is seen in Figure 5.60. Column C0103 is located near the shear wall and this fact reduces the importance of the column. But the case is completely different for plastic approach. When column C0103 is removed, failure of the building takes place before reaching maximum displacement of the original building. Due to this situation discrepancy between the elastic and plastic approaches is high.

In Y direction, failure takes place due to formation of plastic hinges at both ends of columns. High importance of columns (C0106, C0107, C0108, and C0109) which are located under floor with high irregularity in plan, is expected because of the reasons described for Building 1. The most important member for this building is determined as shear wall. But this is not an indicative of the necessity to the shear wall. As seen in the pushover curves (Figure 5.51), in X direction, placement of shear wall does not increase the capacity of the building because the off-centered single shear wall generates a large torsional mode. Since the base shear is mainly carried by the shear wall, its importance is high in X direction. Placement of shear walls is not always improvement for the buildings as seen in this example. Due to presence of shear wall, structure fails prior to full energy dissipation capacity is used. Importance of shear wall is high in Y direction also. When shear wall is removed during pushover analysis in Y direction, building behavior completely changes due to dead load distributions.

Figures 5.61 and 5.62 display the distribution of importance factors along members in X and Y Directions, respectively. In the graph in both directions high importance of column C0109 and shear wall SW0101 are observed.

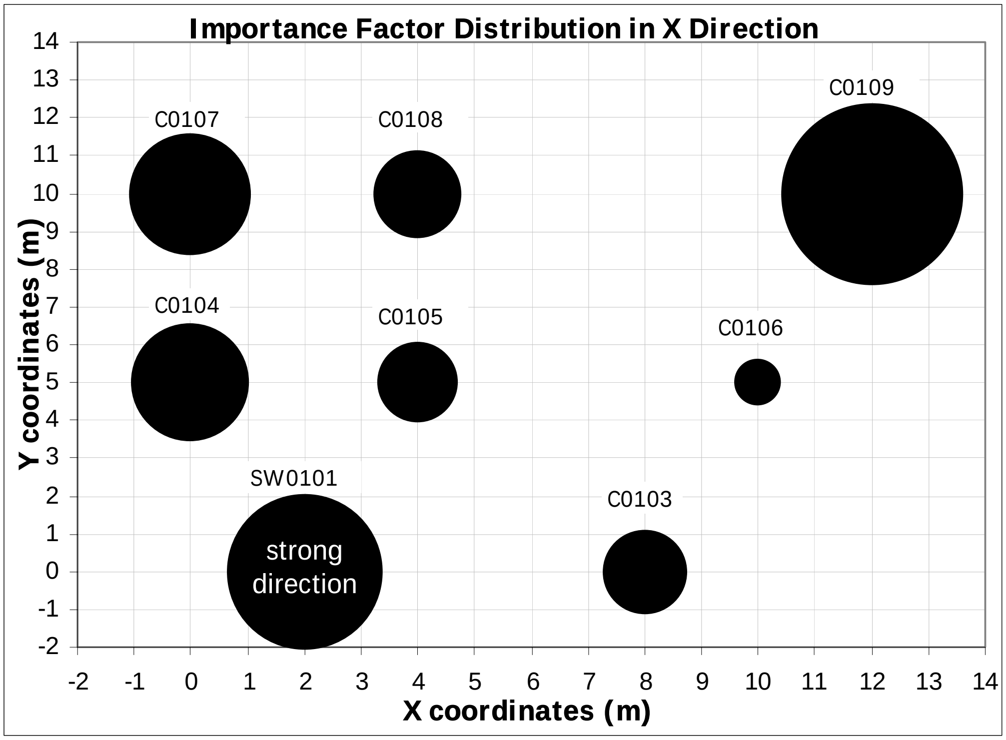

Figure 5.61 Importance Factor Distribution in X Direction for Building 2

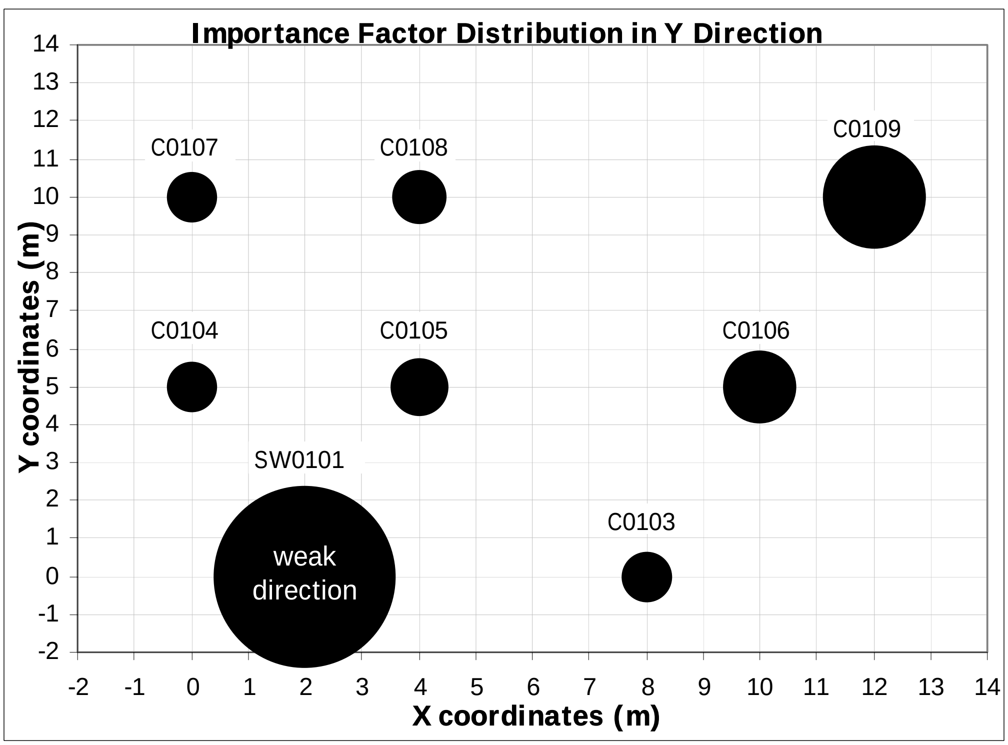

Figure 5.62 Importance Factor Distribution in Y Direction for Building 2

5.3.3 BUILDING 3

Modified version of Building 1, for which the details are presented in section 5.3.1, is evaluated in this section. Columns C0107, C0108 are removed and shear wall with section type SW01 is placed instead of them. The details of the shear wall are displayed in Figure 5.41

The X and Y dominant mode shapes used in the analysis are displayed in Figures 5.63 and 5.64, respectively. The pushover curves obtained in X and Y directions are presented in figures 5.65 to 5.80.

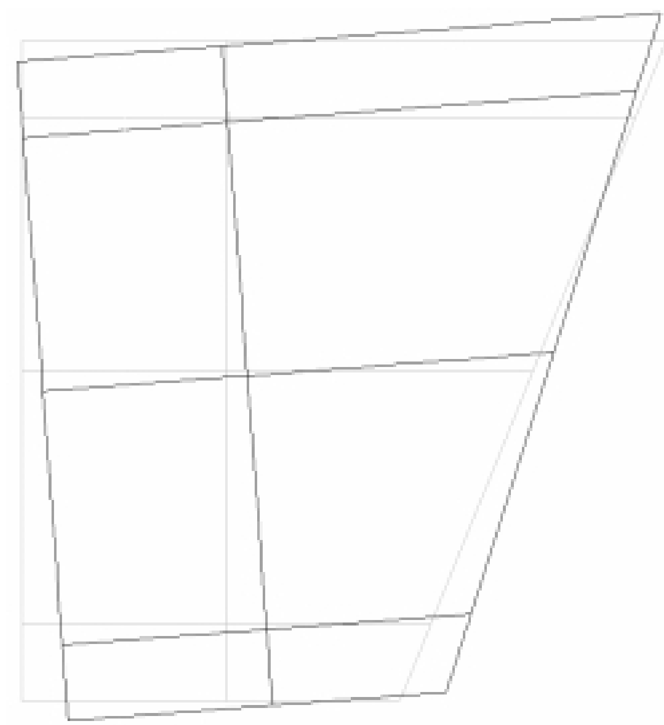

Figure 5.63 Mode Shape in X Dominant Direction for Building 3

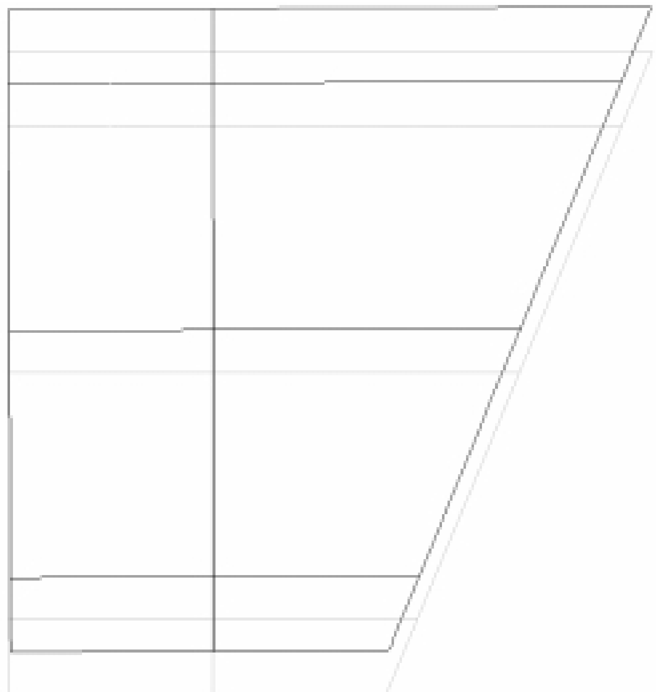

Figure 5.64 Mode Shape in Y Dominant Direction for Building 3

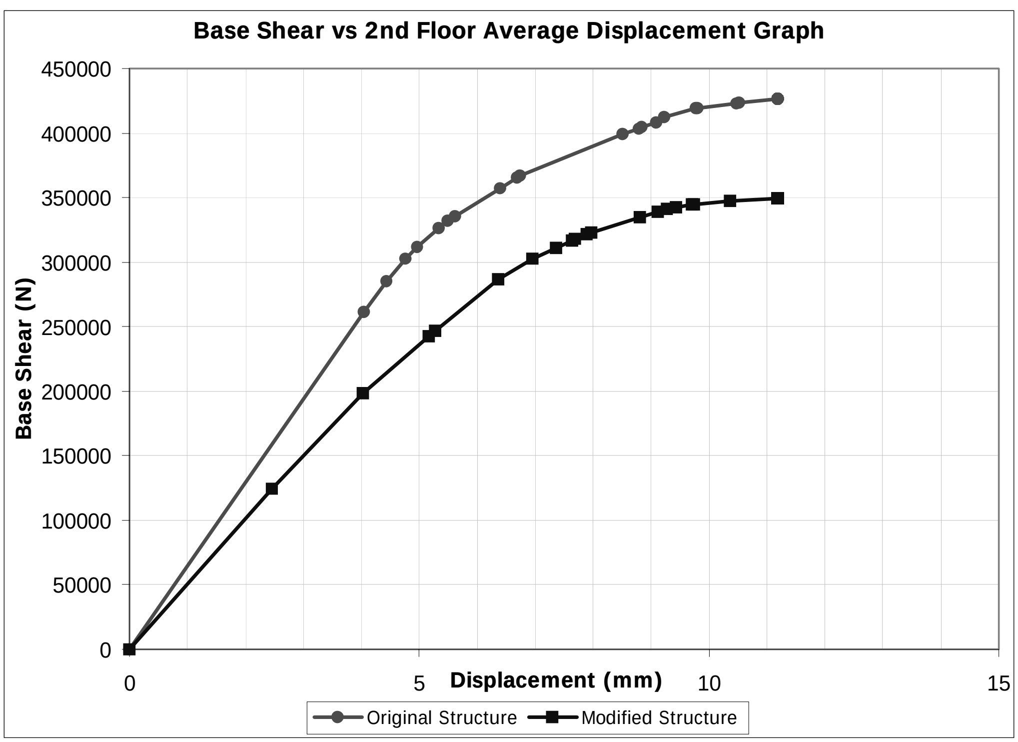

Figure 5.65 (-) X Direction Pushover for Building 3. Removed Member: C0101

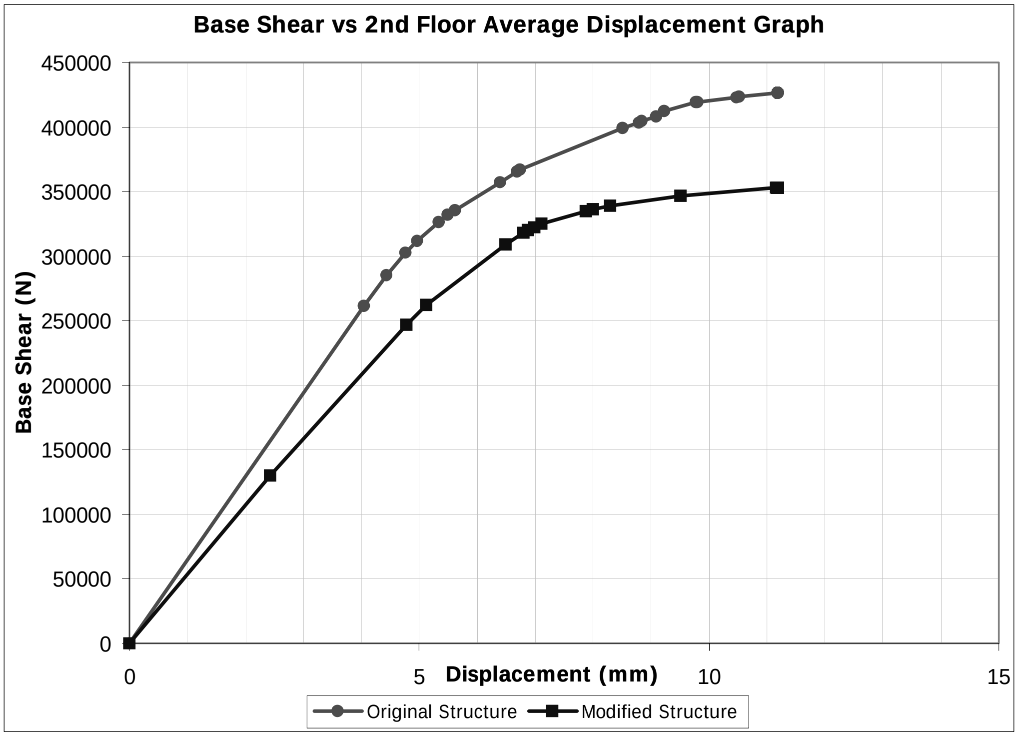

Figure 5.66 (-) X Direction Pushover for Building 3. Removed Member: C0102

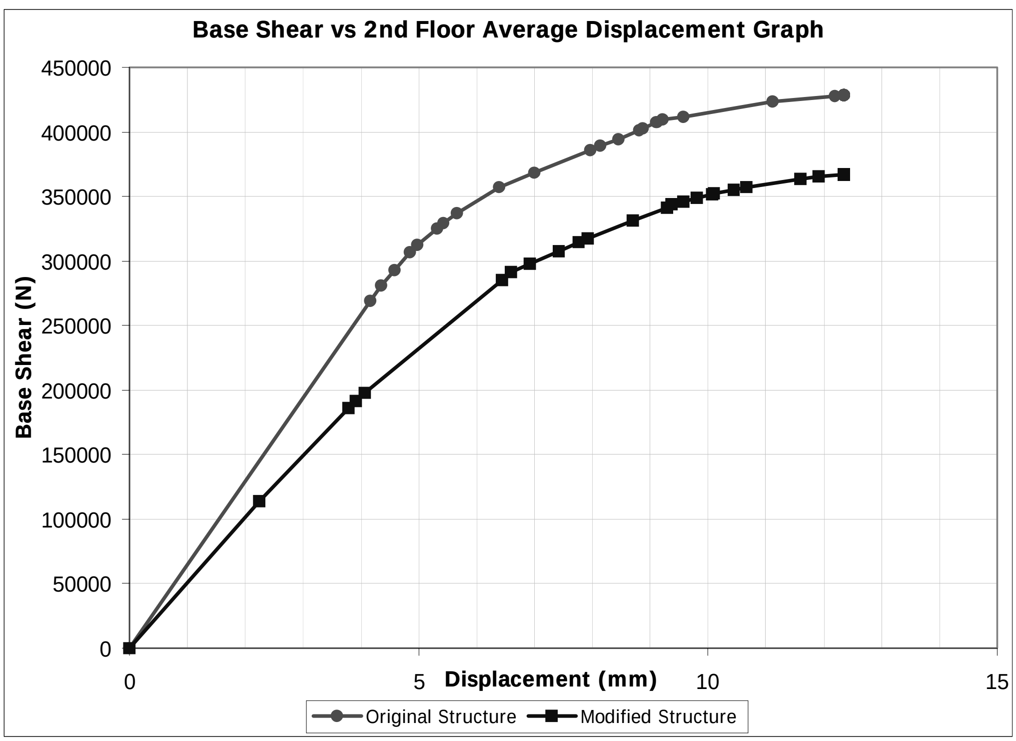

Figure 5.67 (+) X Direction Pushover for Building 3. Removed Member: C0103

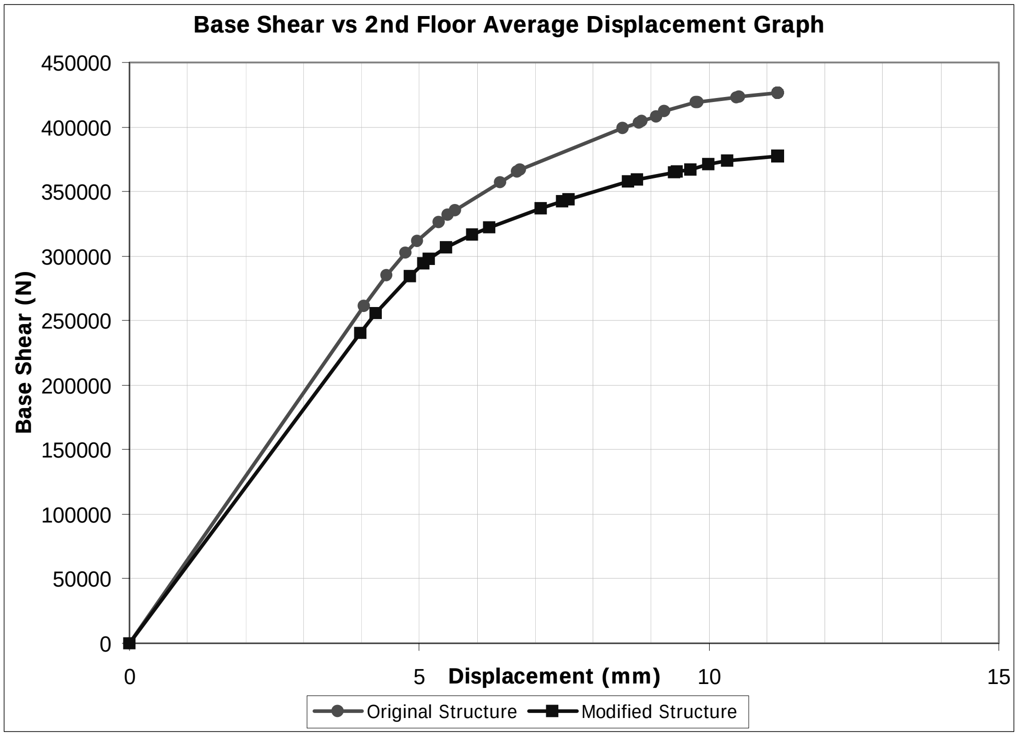

Figure 5.68 (-) X Direction Pushover for Building 3. Removed Member: C0104

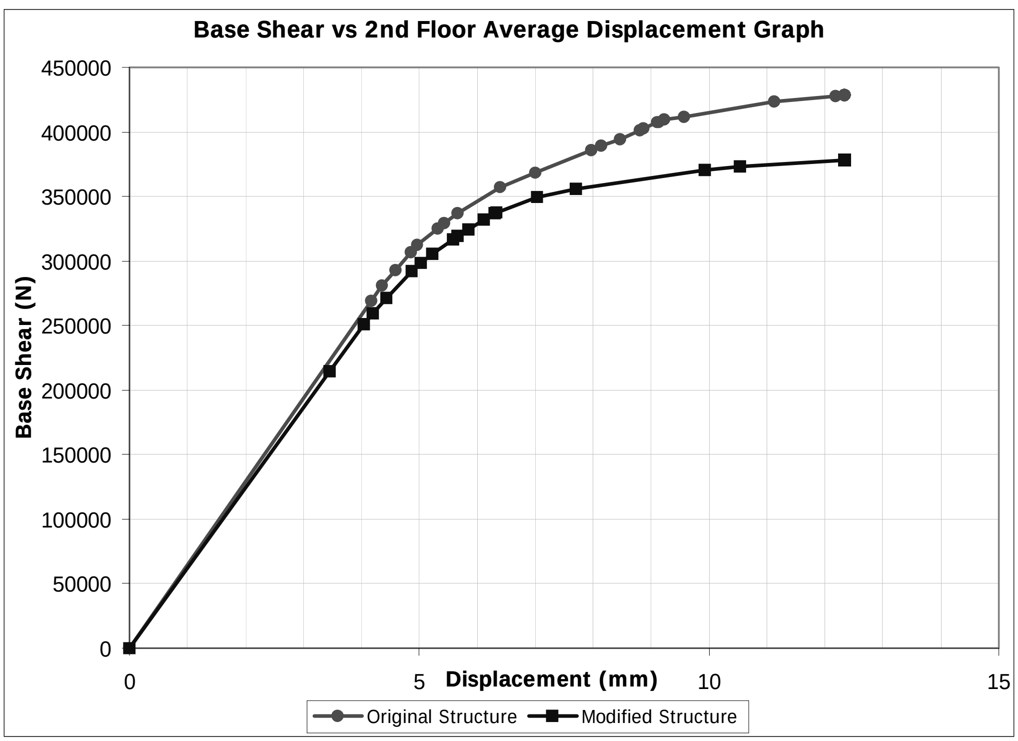

Figure 5.69 (+) X Direction Pushover for Building 3. Removed Member: C0105

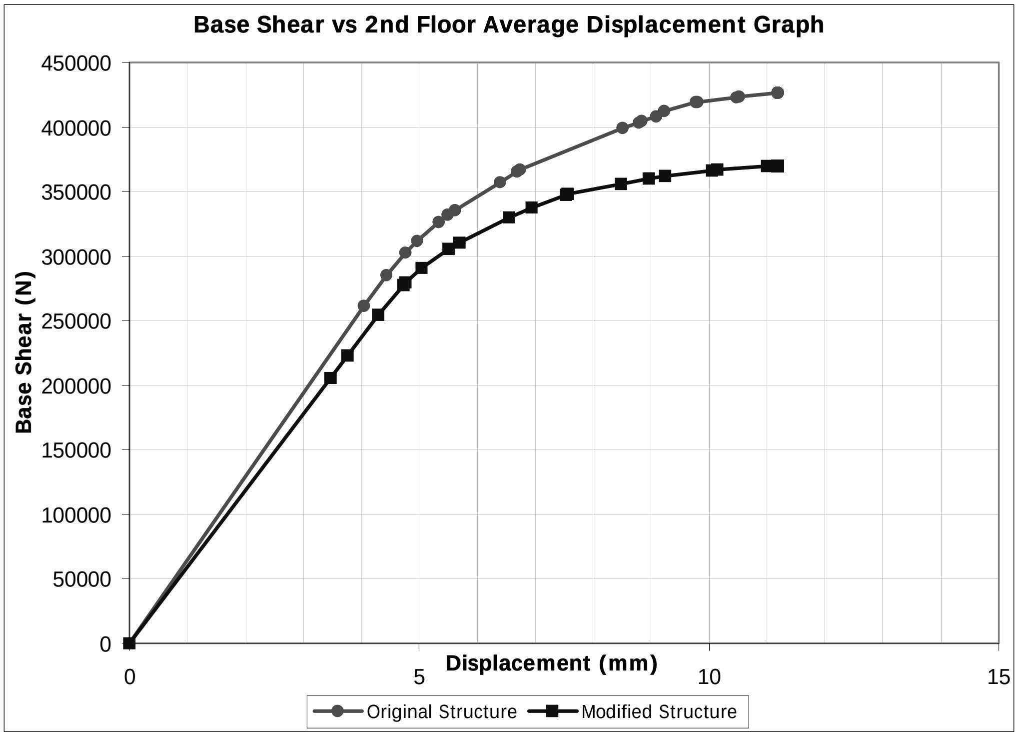

Figure 5.70 (-) X Direction Pushover for Building 3. Removed Member: C0106

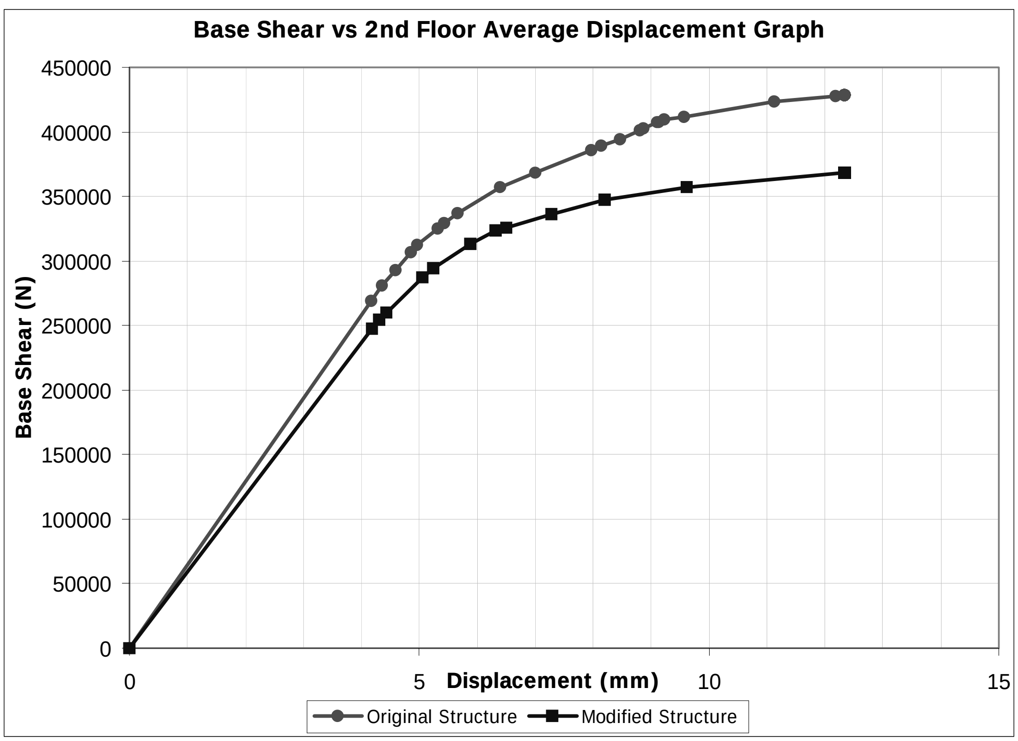

Figure 5.71 (+) X Direction Pushover for Building 3. Removed Member: C0109

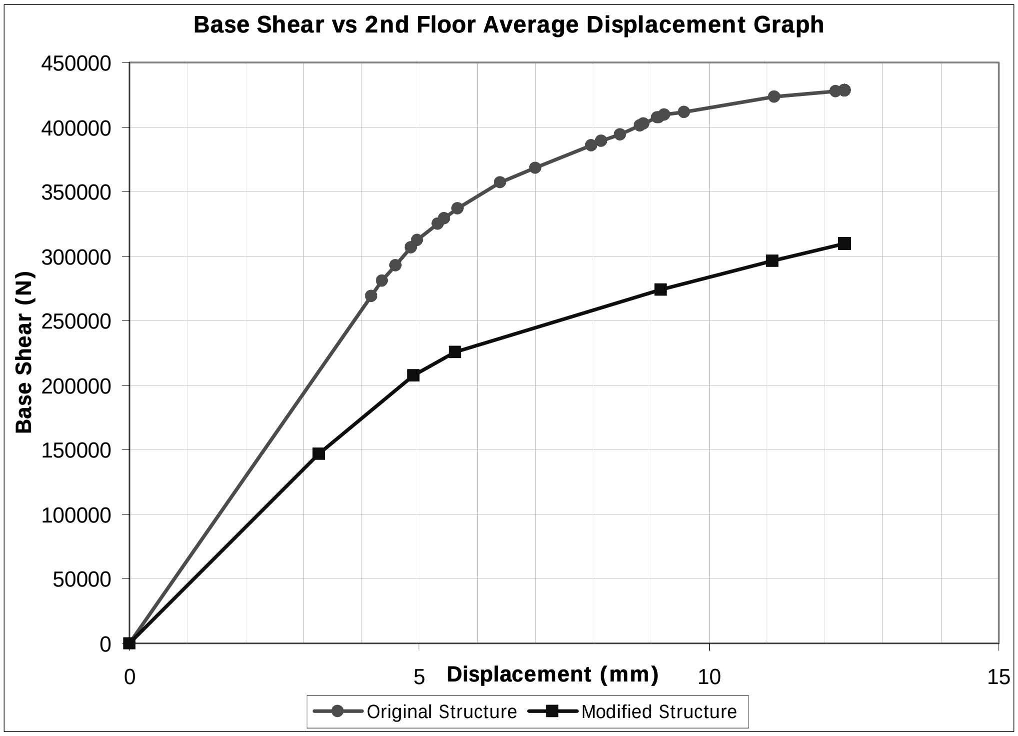

Figure 5.72 (+) X Direction Pushover for Building 3. Removed Member: SW0102

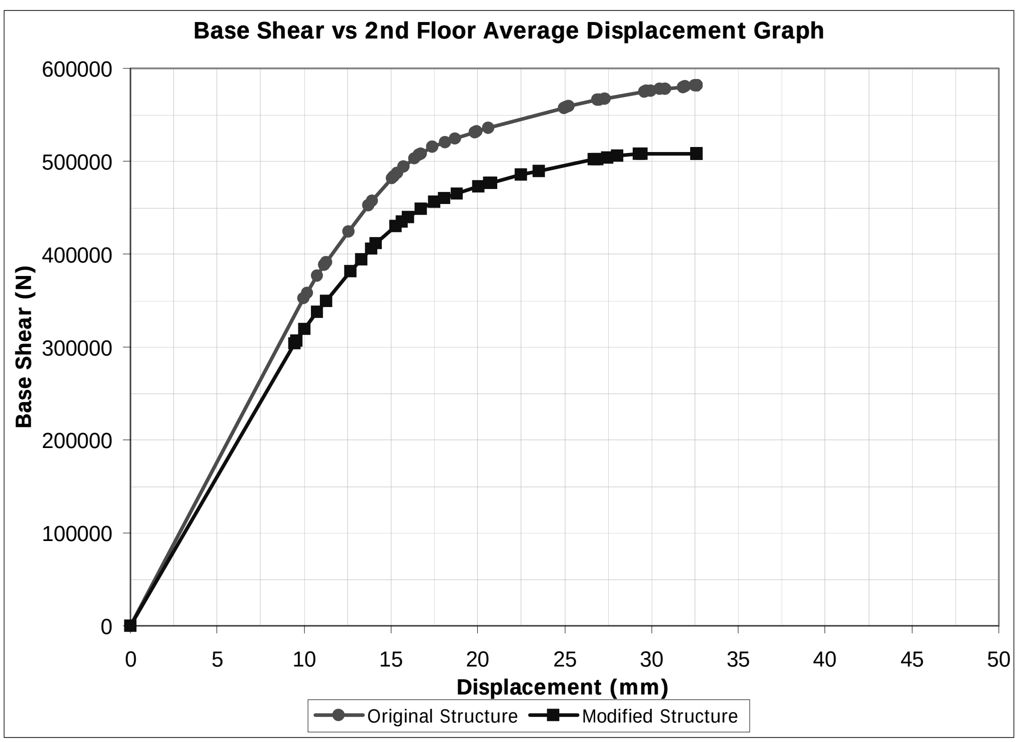

Figure 5.73 (-) Y Direction Pushover for Building 3. Removed Member: C0101

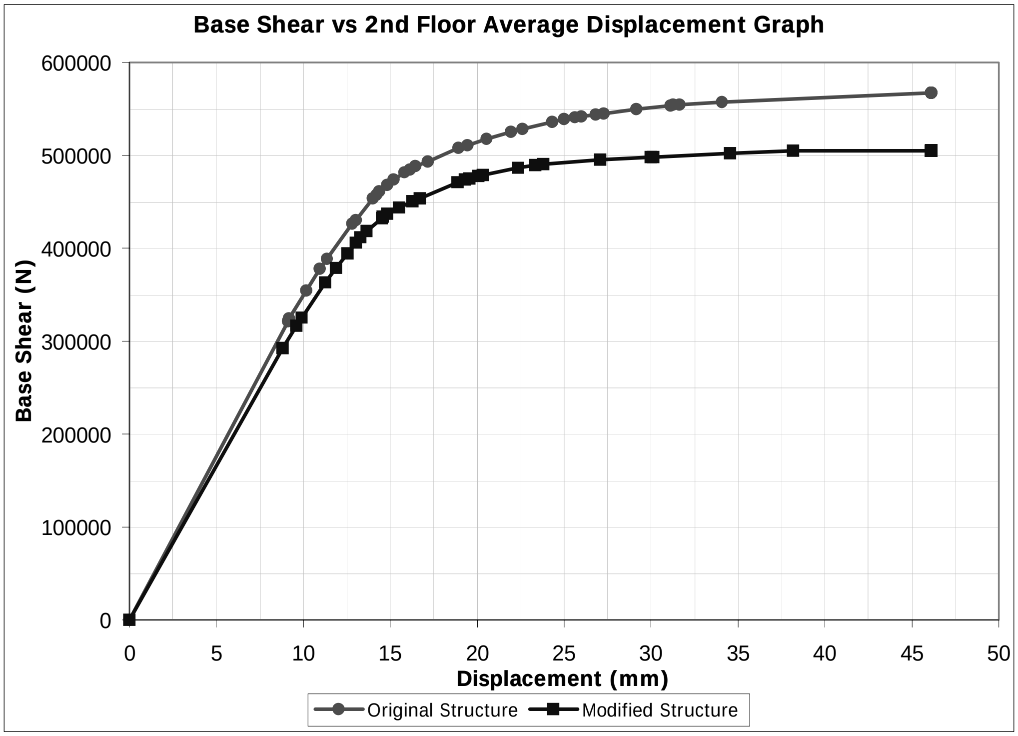

Figure 5.74 (+) Y Direction Pushover for Building 3. Removed Member: C0102

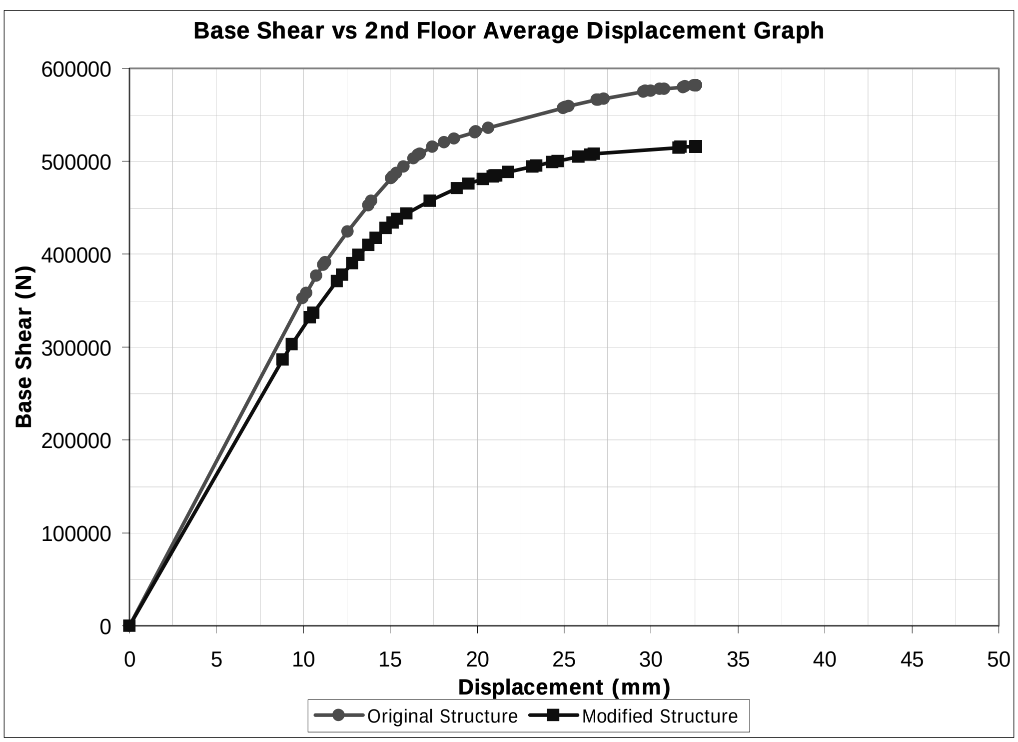

Figure 5.75 (-) Y Direction Pushover for Building 3. Removed Member: C0103

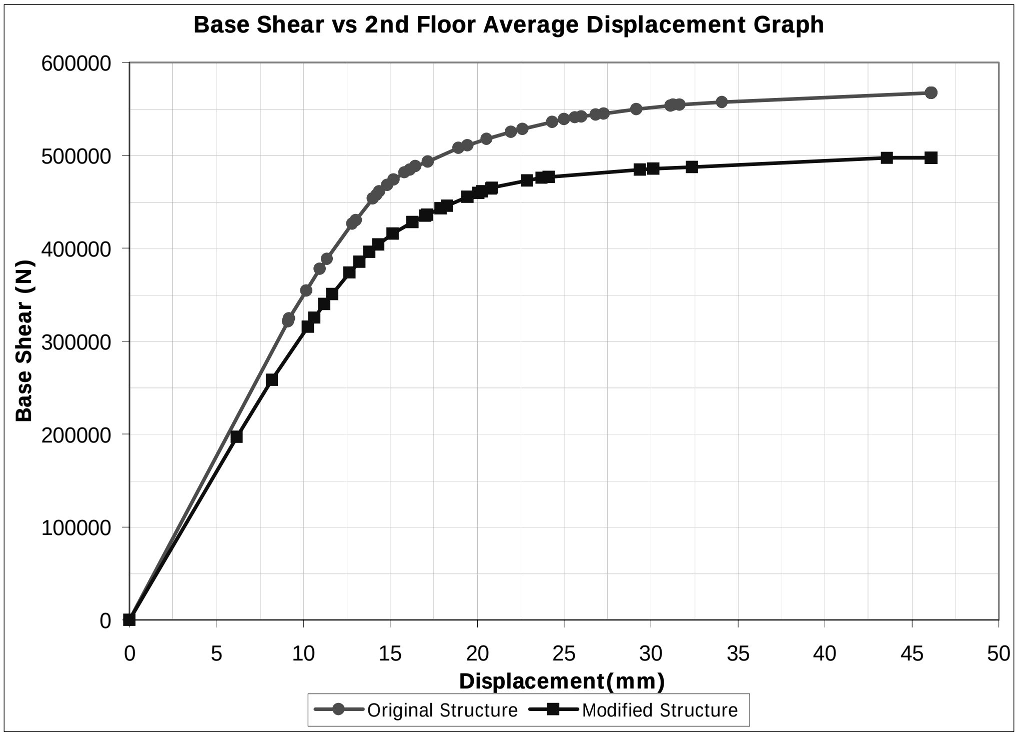

Figure 5.76 (+) Y Direction Pushover for Building 3. Removed Member: C0104

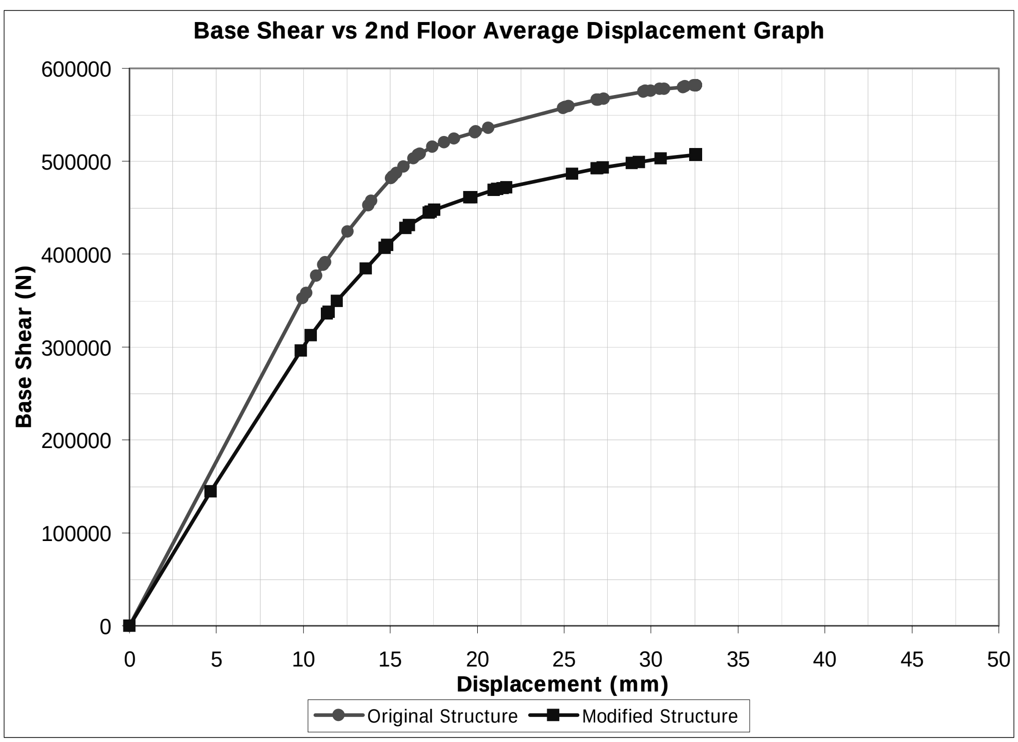

Figure 5.77 (-) Y Direction Pushover for Building 3. Removed Member: C0105

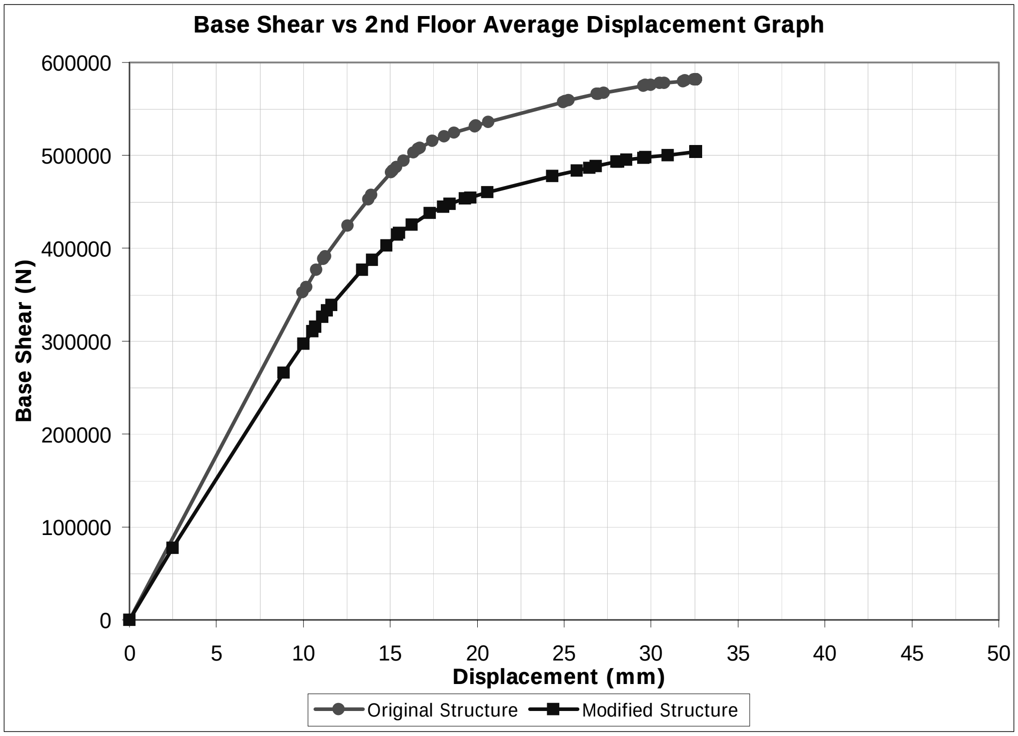

Figure 5.78 (-) Y Direction Pushover for Building 3. Removed Member: C0106

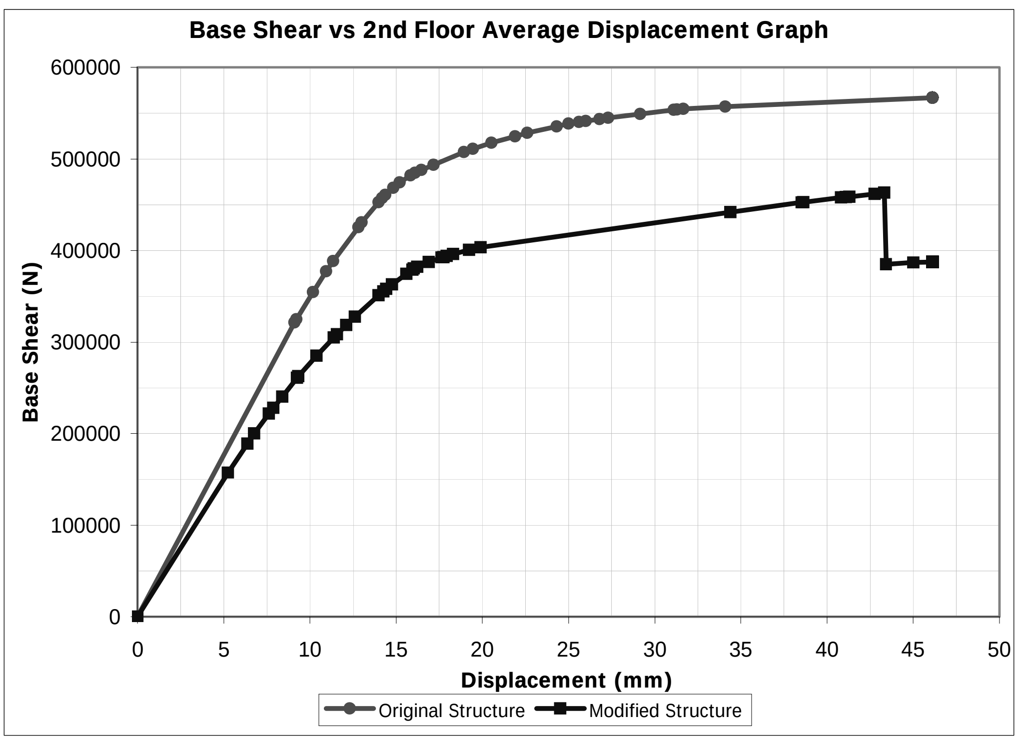

Figure 5.79 (+) Y Direction Pushover for Building 3. Removed Member: C0109

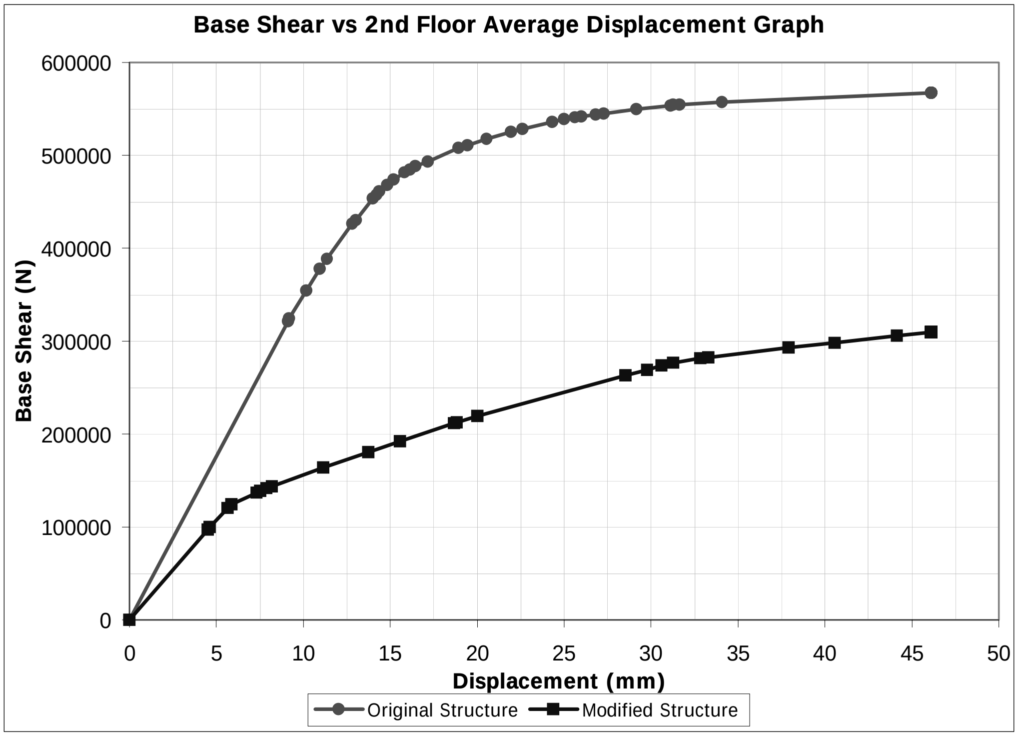

Figure 5.80 (+) Y Direction Pushover for Building 3. Removed Member:SW0102

Discussion of the Results

After pushover analyses are conducted in both directions, importance factors are determined with the methodology described in section 2.2.3.5. Determined importance factors for all base members are displayed in Table 5.7 for elastic and plastic approaches.

Table 5.7 Importance Factors for Elastic and Plastic Approaches

	Importance Factors			
	Elastic Approach		Plastic Approach	
Member	X Direction (EX)	Y Direction (EY)	X Direction (PX)	Y Direction (PY)
C0101	0.218	0.090	0.198	0.110
C0102	0.173	0.063	0.163	0.087
C0103	0.219	0.077	0.189	0.100
C0104	0.065	0.095	0.093	0.116
C0105	0.042	0.127	0.078	0.134
C0106	0.084	0.107	0.100	0.143
C0109	0.086	0.149	0.112	0.216
SW0102	0.306	0.389	0.319	0.517

The ratio of importance factors obtained by plastic approach to importance factors obtained by plastic approach show the difference in two evaluation methods. Results are presented in Table 5.8.

Table 5.8 Importance Factor Comparison for Elastic and Plastic Approaches

Importance Factor Comparison		
Member	**X Direction**	**Y Direction**
C0101	91%	122%
C0102	94%	139%
C0103	87%	129%
C0104	144%	123%
C0105	185%	106%
C0106	119%	133%
C0109	131%	145%
SW0102	104%	133%

Discrepancy in the results shown in table 5.8 indicates that the plastic and elastic approaches are not substitute of each other.

Figure 5.81 display the distribution of importance factors along members in X and Y directions for elastic and plastic approaches.

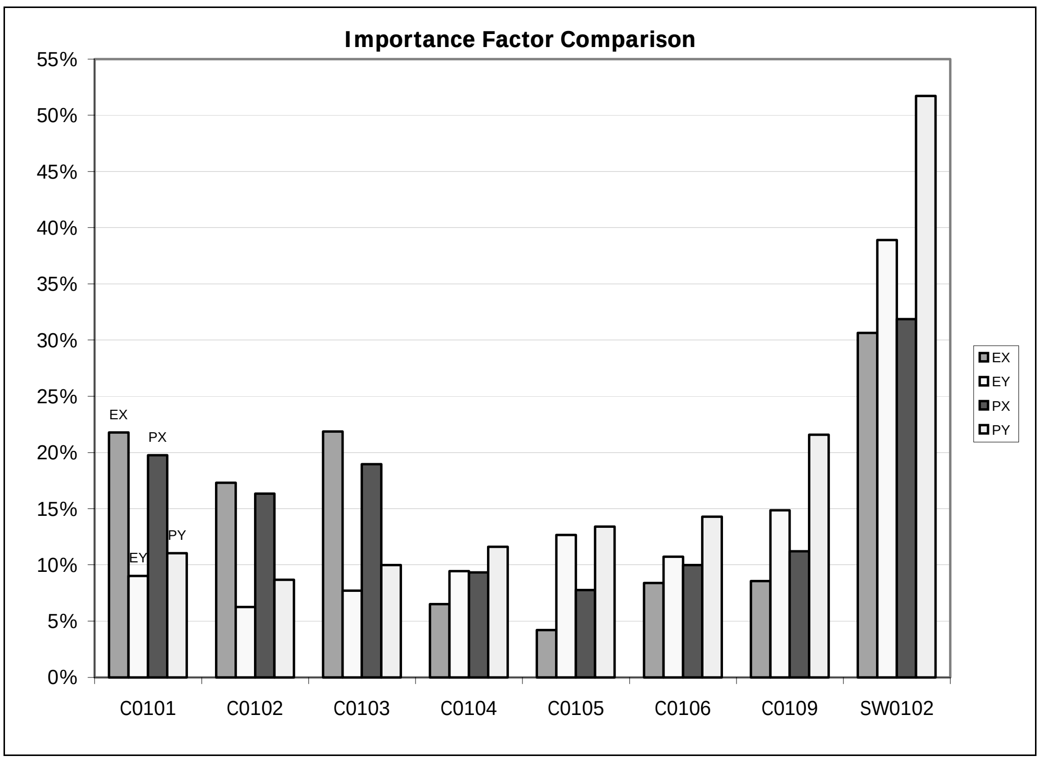

Figure 5.81 Member Importance Factors for Building 3

The comparison of importance factor distribution is studied, it is observed that columns C0104 to C0109 have high importance in Y direction and columns C0101 to C0103 have high importance in X direction. Importance of shear wall is high as in Building 2.

As X dominant direction mode shape indicates (shown in Figure 5.63) placement of shear wall generates torsion. The building rotates approximately about shear wall location. Due to this behavior, the importance of columns C0101 to C0103 increases considerably when compared with Building 1. Unlike column C0103 in Building 2, column C0109 has high importance although it is located near the shear wall. Location of a member is another basic attribute that effect importance of members. Introducing shear wall at the longer edge of the building in X direction does not enhance the seismic behavior of the building although stiffness center is shifted closer to the mass center which is located towards the newly introduced shear wall. When compared with Building 1, shear capacity of the building reduced considerably with the placement of the shear wall. But by this placement shear failures are avoided which is an improvement in other aspect.

Figures 5.43 and 5.44 display the distribution of importance factors along members in X and Y Directions, respectively. In the graph in both directions relatively high importance of columns C0101, C0102 and C0103 and shear wall SW0101 are observed. Columns C0104, C0105 and C0106 have similar importance in both directions.

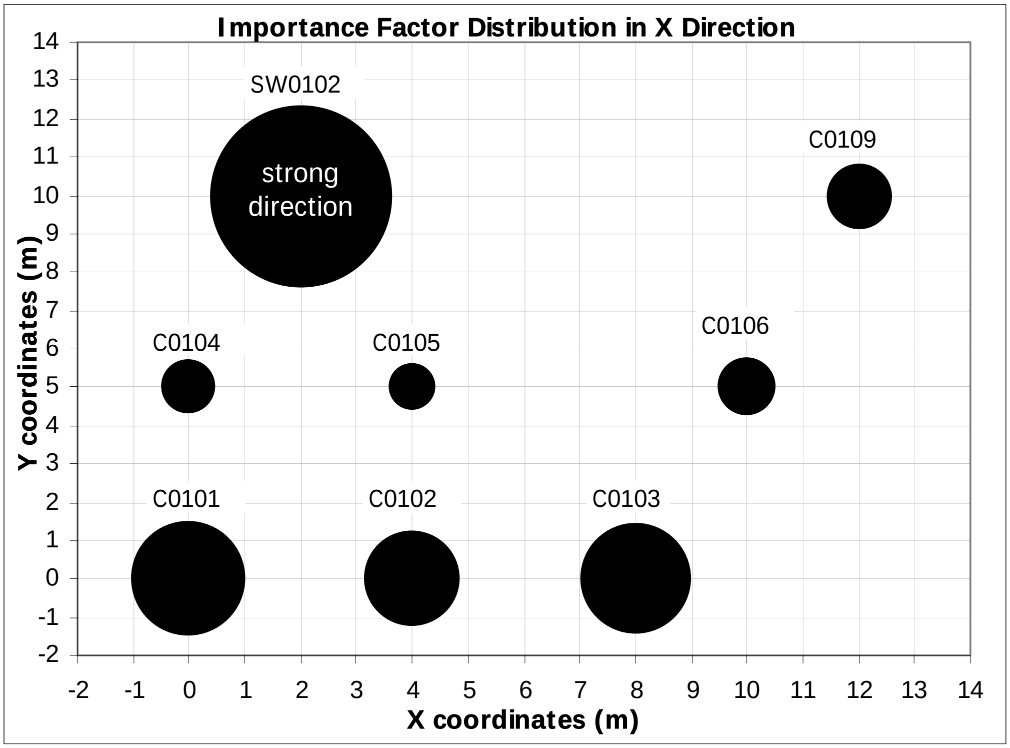

Figure 5.82 Importance Factor Distribution in X Direction for Building 3

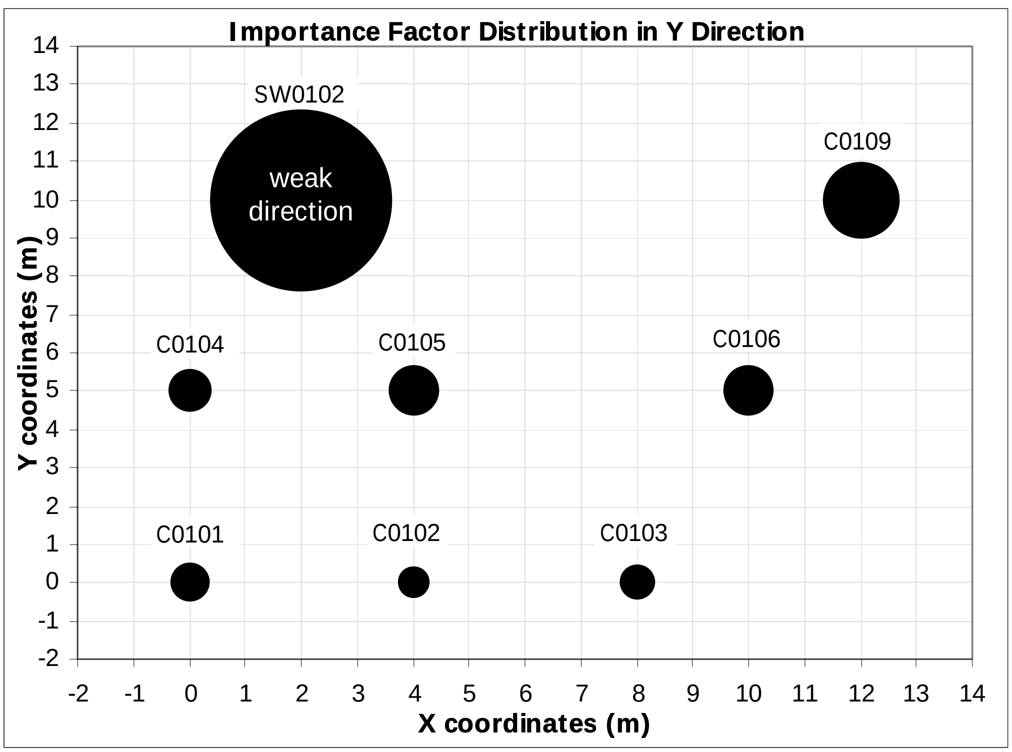

Figure 5.83 Importance Factor Distribution in Y Direction for Building 3

5.3.4 BUILDING 4

In this section, building for which the details are presented in Figures 5.84 to 5.98, is evaluated. As seen in the figures the building has wide columns and shear walls. The details of the building are as follows:

- Building has 3 stories and 3 bays in each direction.
- Details of the section types used in the building are displayed in Figures 5.84 to 5.94. Table 5.9 display list of members with assigned section types.
- Building 3D Model and floor layout are displayed in Figures 5.95 to 5.98.
- All floor heights: 4m
- Building has floor and vertical irregularities

The X and Y dominant mode shapes used in the pushover analyses are displayed in Figures 5.99 and 5.100, respectively. The pushover curves obtained in X and Y directions are presented in figures 5.101 to 5.126.

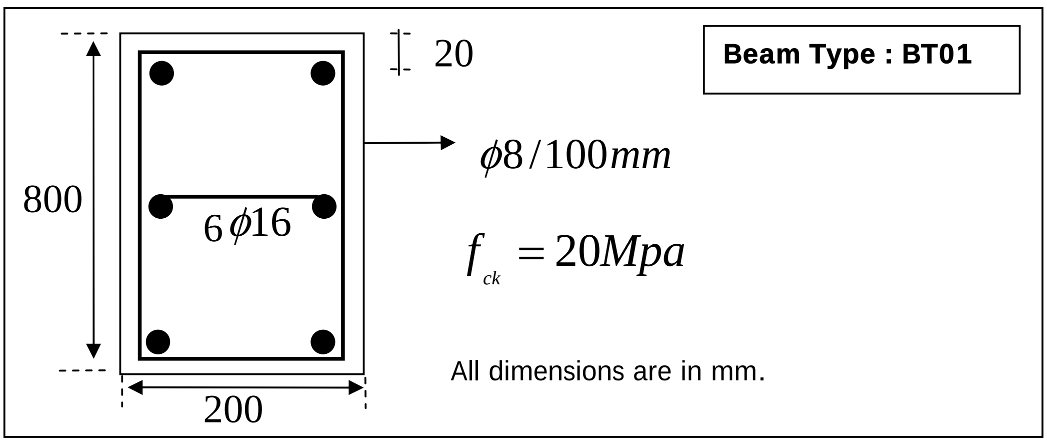

Figure 5.84 Details of Beam Type BT01

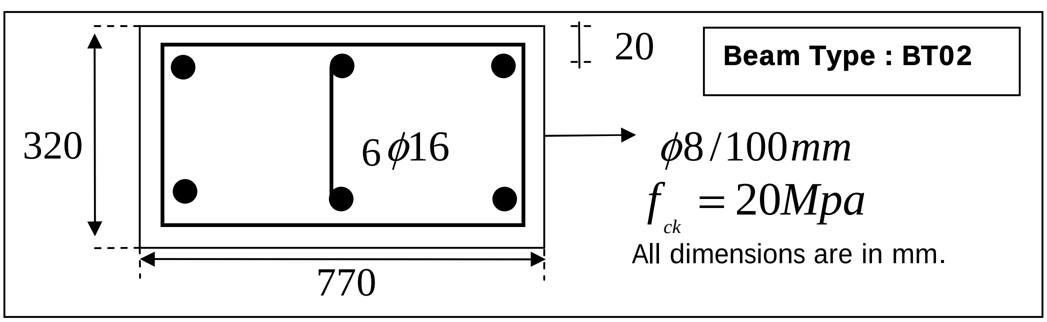

Figure 5.85 Details of Beam Type BT02

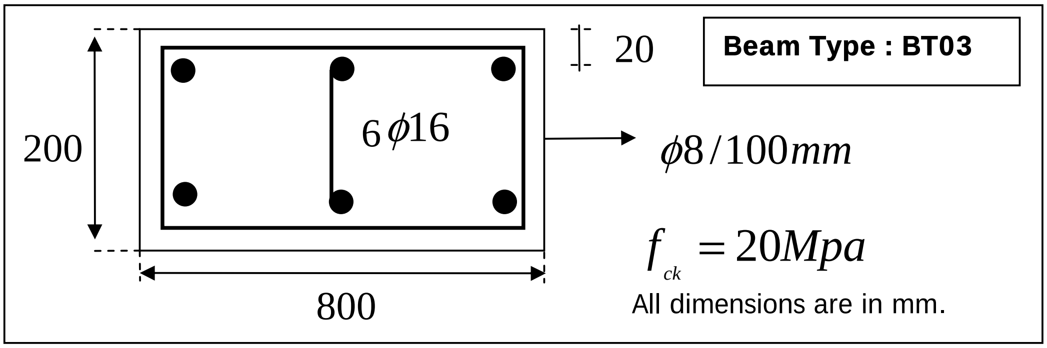

Figure 5.86 Details of Beam Type BT03

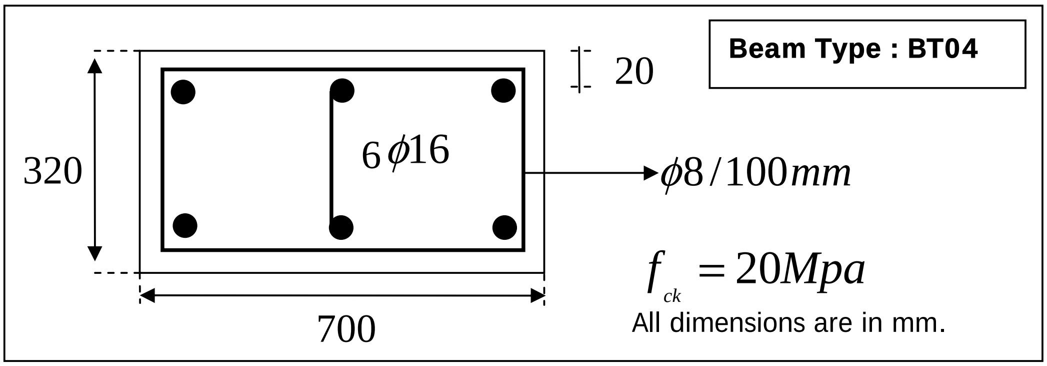

Figure 5.87 Details of Beam Type BT04

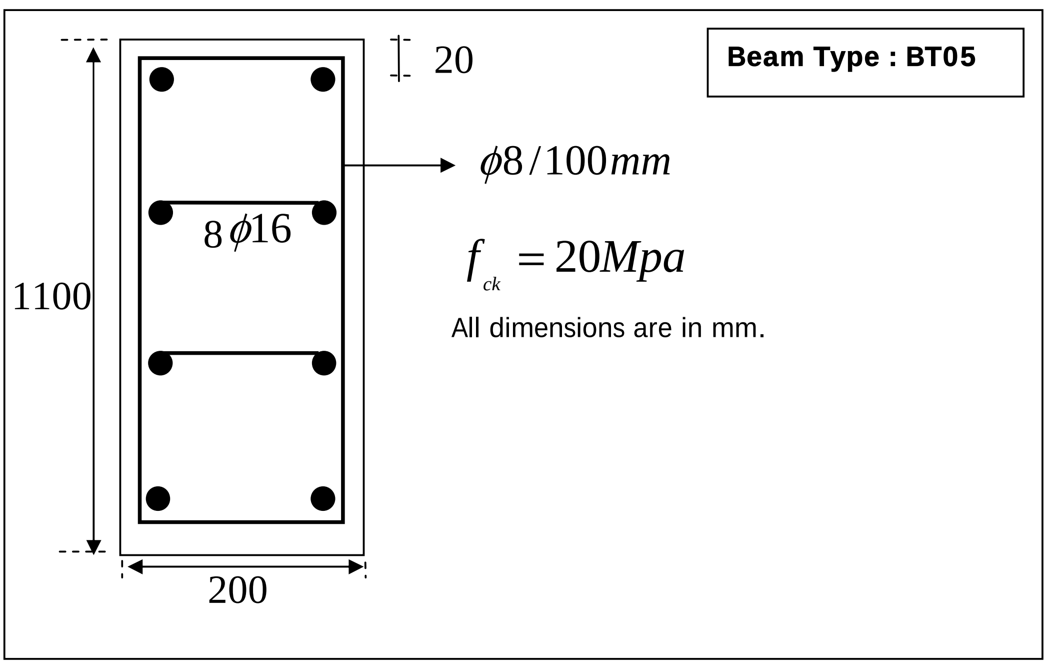

Figure 5.88 Details of Beam Type BT05

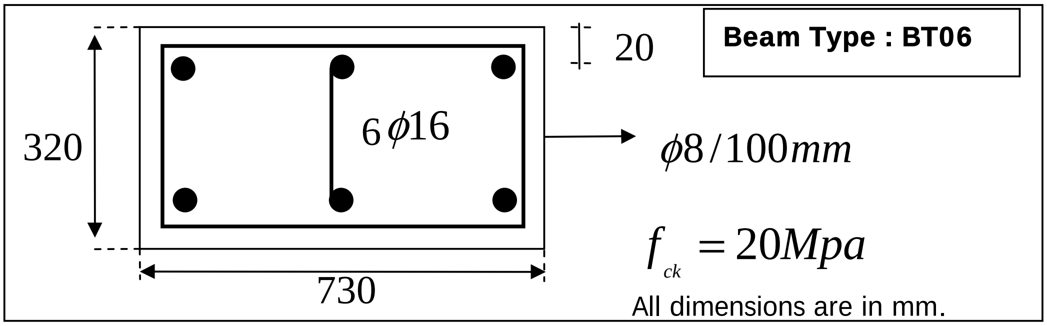

Figure 5.89 Details of Beam Type BT06

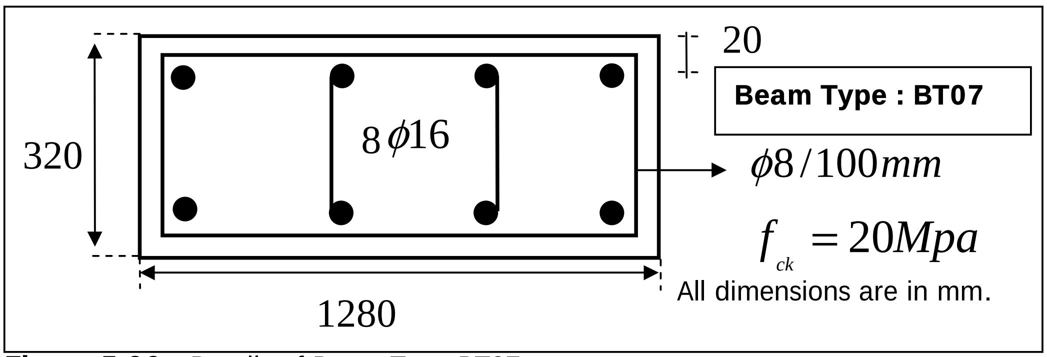

Figure 5.90 Details of Beam Type BT07

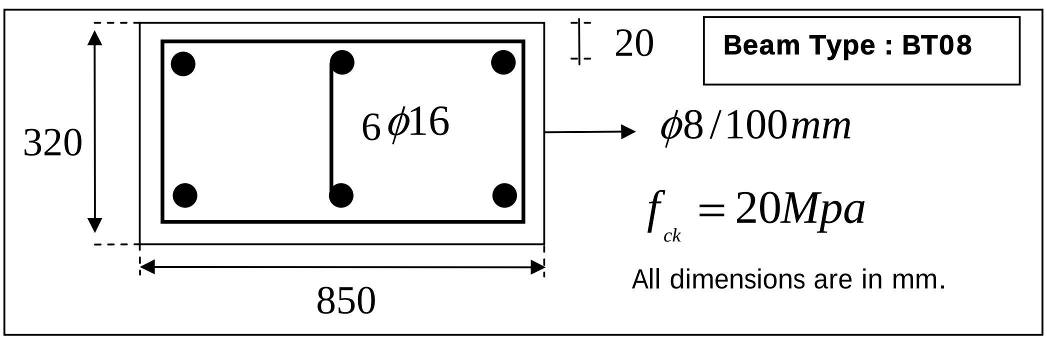

Figure 5.91 Details of Beam Type BT08

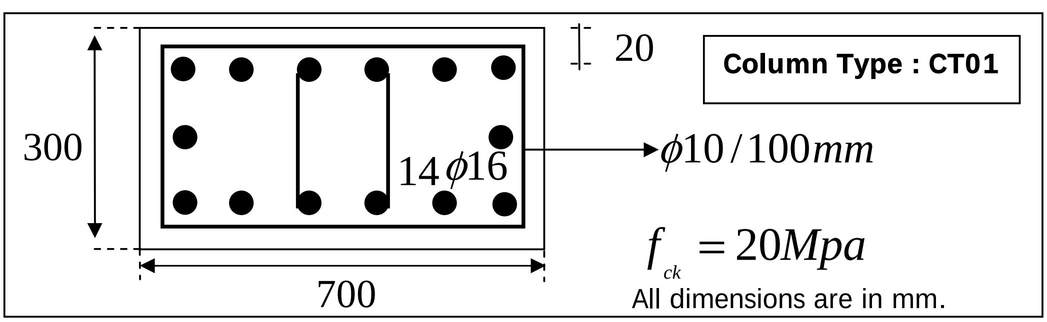

Figure 5.92 Details of Column Type CT01

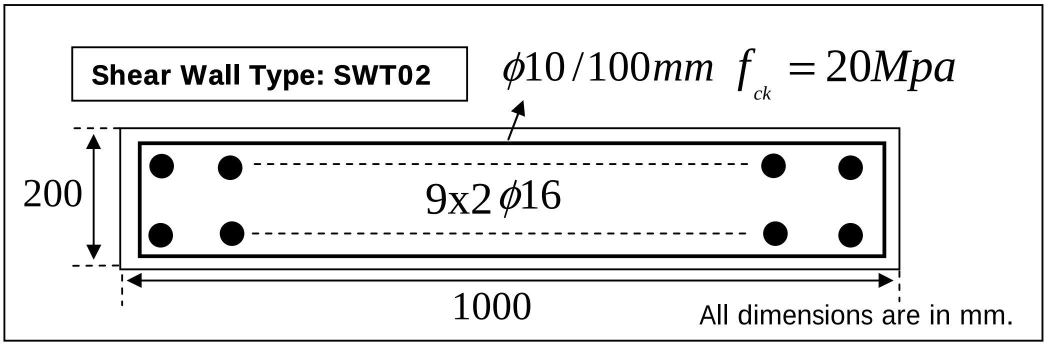

Figure 5.93 Details of Shear Wall Type SWT02

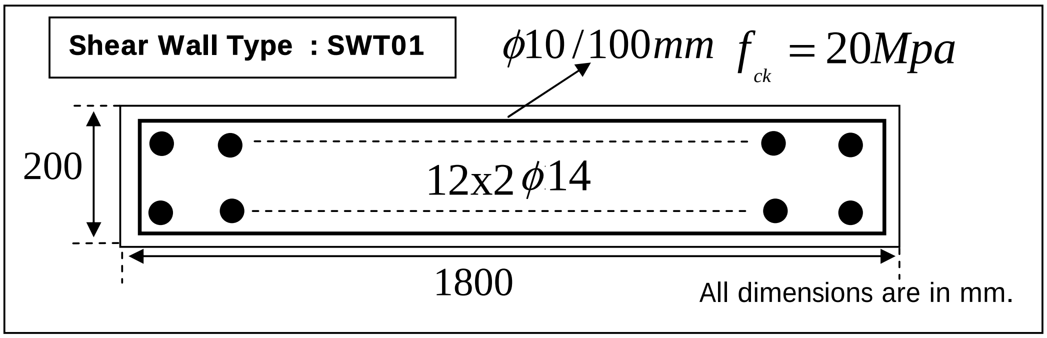

Figure 5.94 Details of Shear Wall Type SWT01

Table 5.9 List of Members with assigned Section Types

1st Floor Beams

Member Label	Section Type
B0101	BT01
B0102	BT01
B0103	BT01
B0104	BT01
B0105	BT01
B0106	BT01
B0107	BT01
B0108	BT04
B0109	BT01
B0110	BT06
B0111	BT07
B0112	BT01
B0114	BT02
B0115	BT02
B0116	BT02
B0117	BT01
B0118	BT08
B0119	BT01
B0120	BT01
B0121	BT01
B0122	BT01
B0123	BT01
B0127	BT01
B0128	BT01

1st Floor Columns

Label Member	Section Type
C0101	CT01
C0102	CT01
C0103	CT01
C0104	CT01
C0105	CT01
C0106	CT01
C0107	CT01
C0108	CT01
C0109	CT01
C0110	CT01

1st Floor Shear Walls

Member Label	Section Type
SW0101	SWT01
SW0102	SWT02
SW0103	SWT02

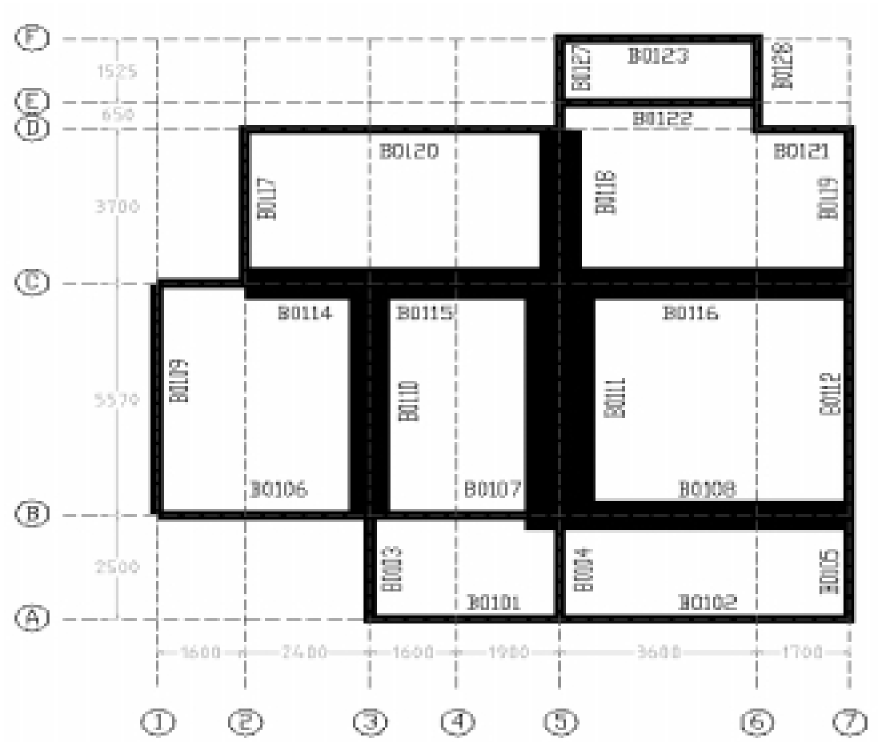

Figure 5.95 First Floor Beam Layout of Building 4

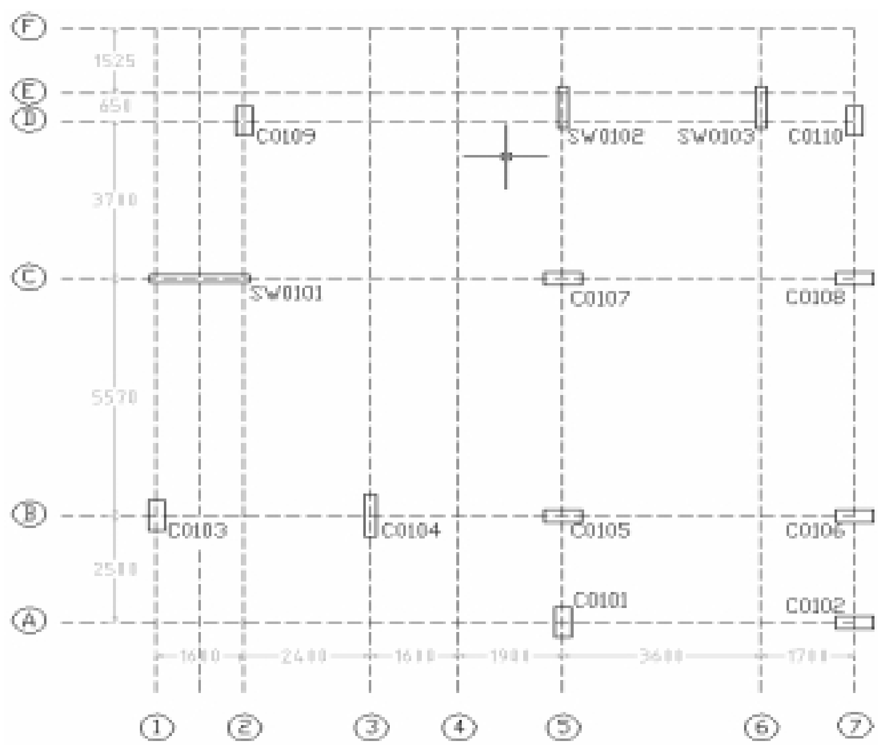

Figure 5.96 Base Floor Column & Shear Wall Layout of Building 4

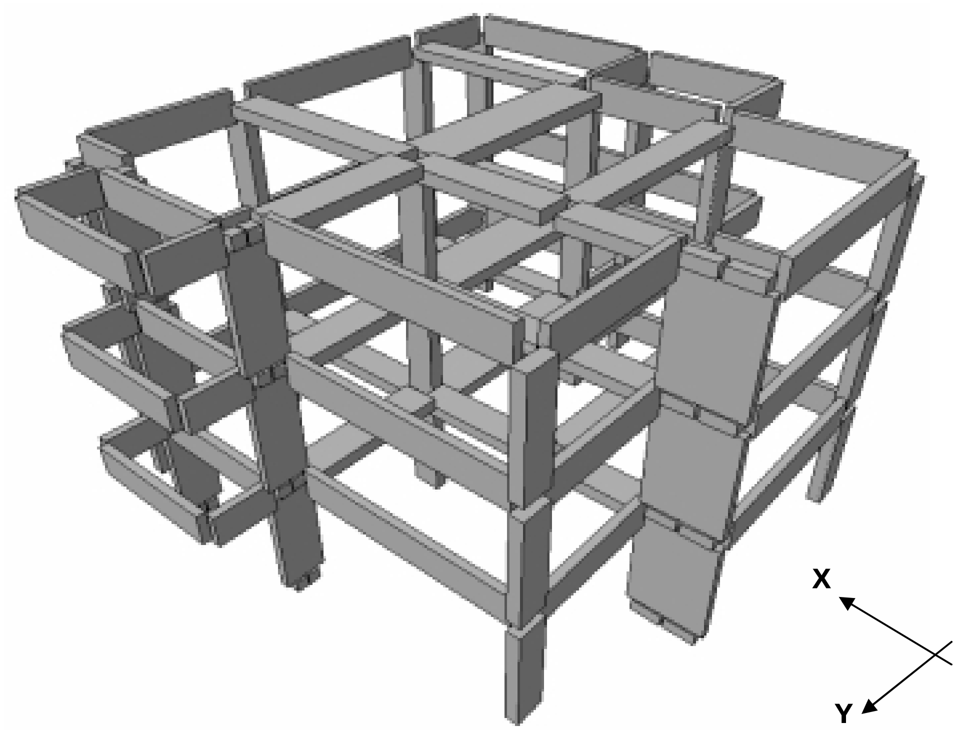

Figure 5.97 3D Model of Building 4

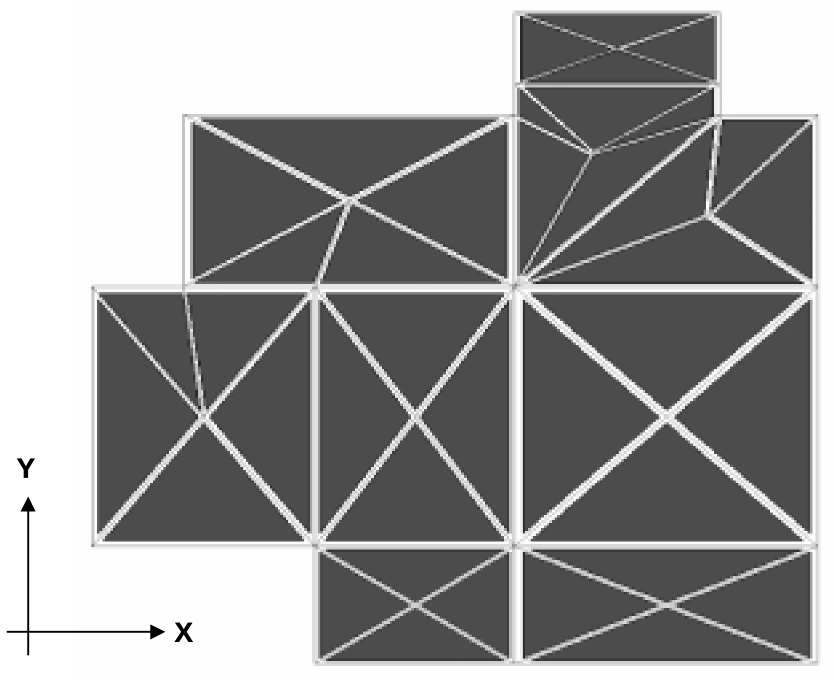

Figure 5.98 Floor Plan of Building 4, with Shells

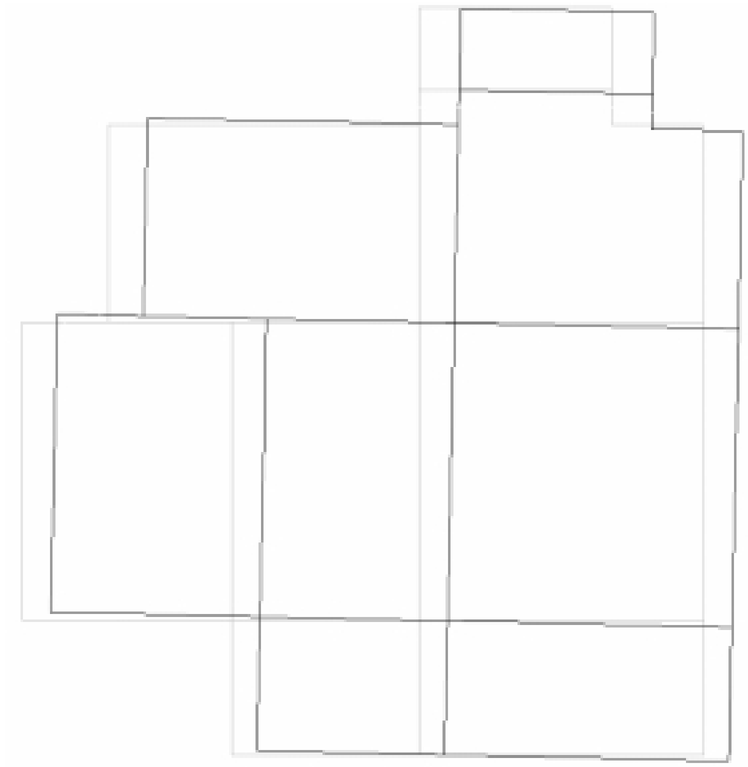

Figure 5.99 Mode Shape in X Dominant Direction for Building 4

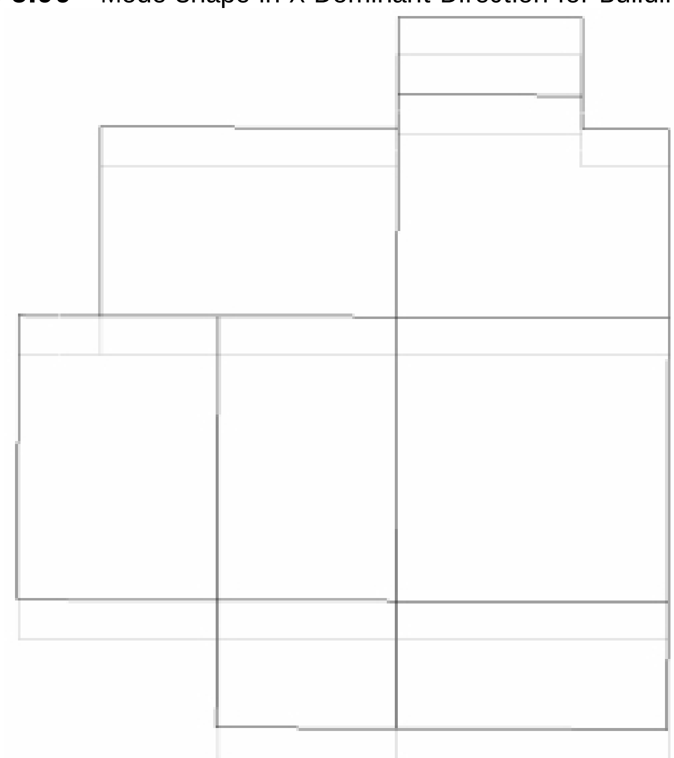

Figure 5.100 Mode Shape in Y Dominant Direction for Building 4

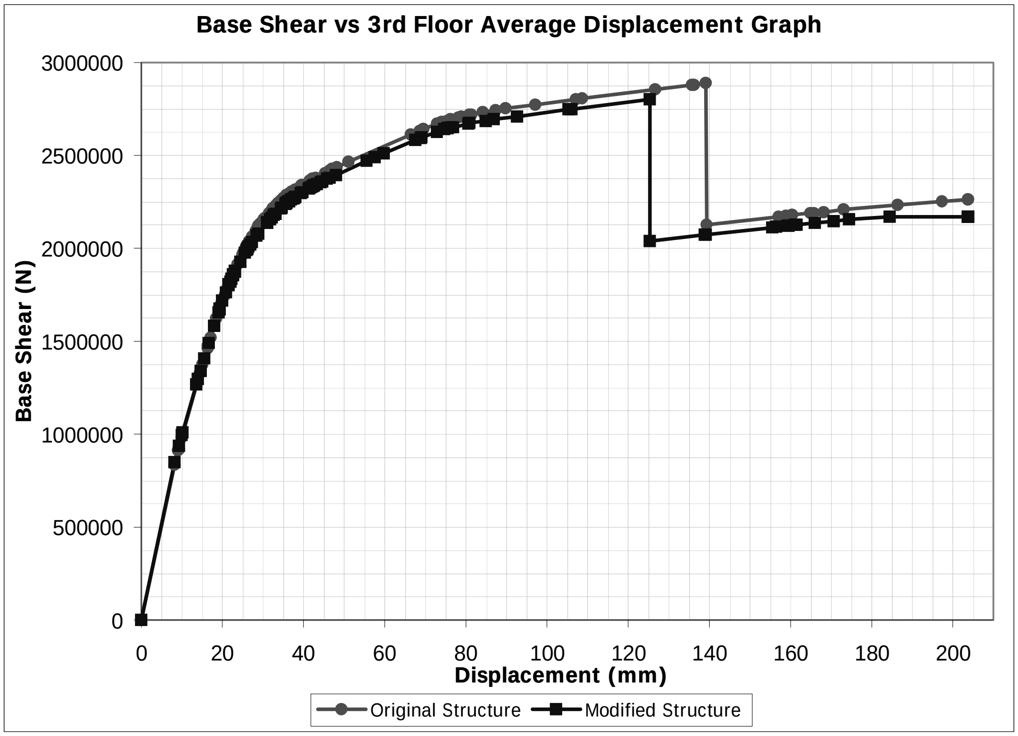

Figure 5.101 (+) X Direction Pushover for Building 4. Removed Member: C0101

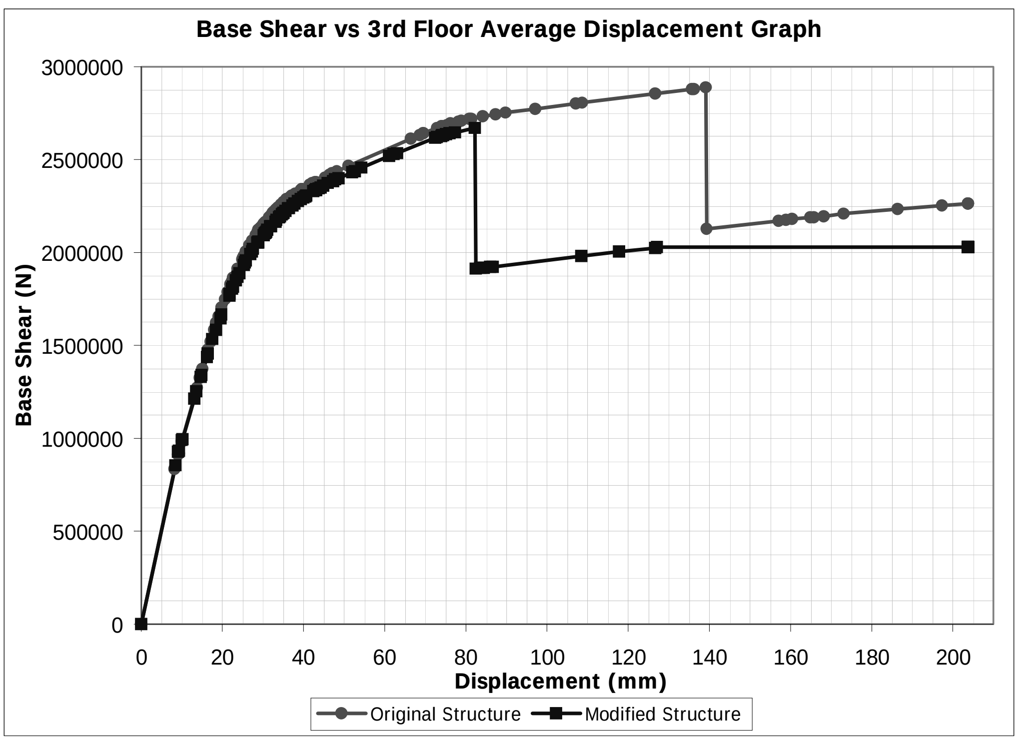

Figure 5.102 (+) X Direction Pushover for Building 4. Removed Member: C0102

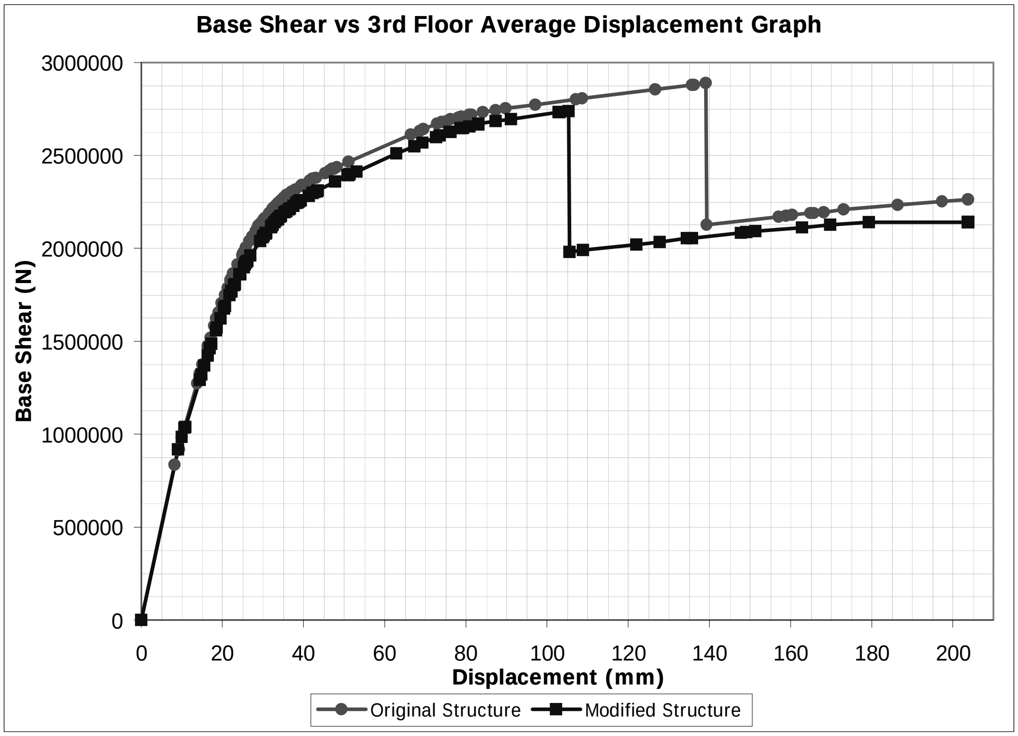

Figure 5.103 (+) X Direction Pushover for Building 4. Removed Member: C0103

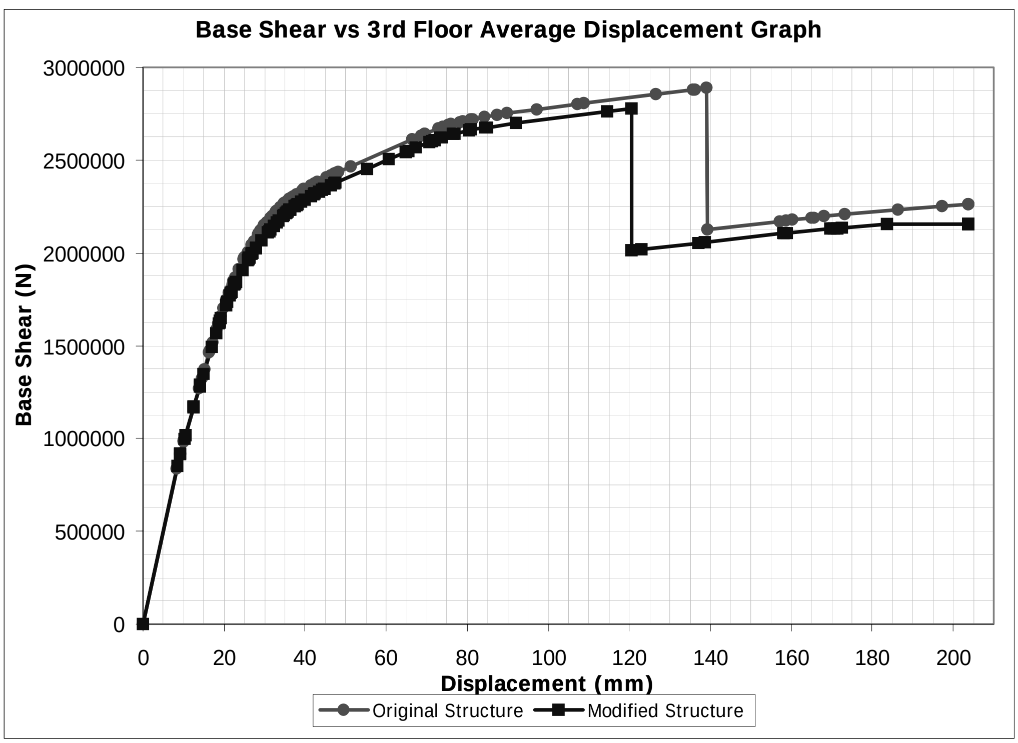

Figure 5.104 (+) X Direction Pushover for Building 4. Removed Member: C0104

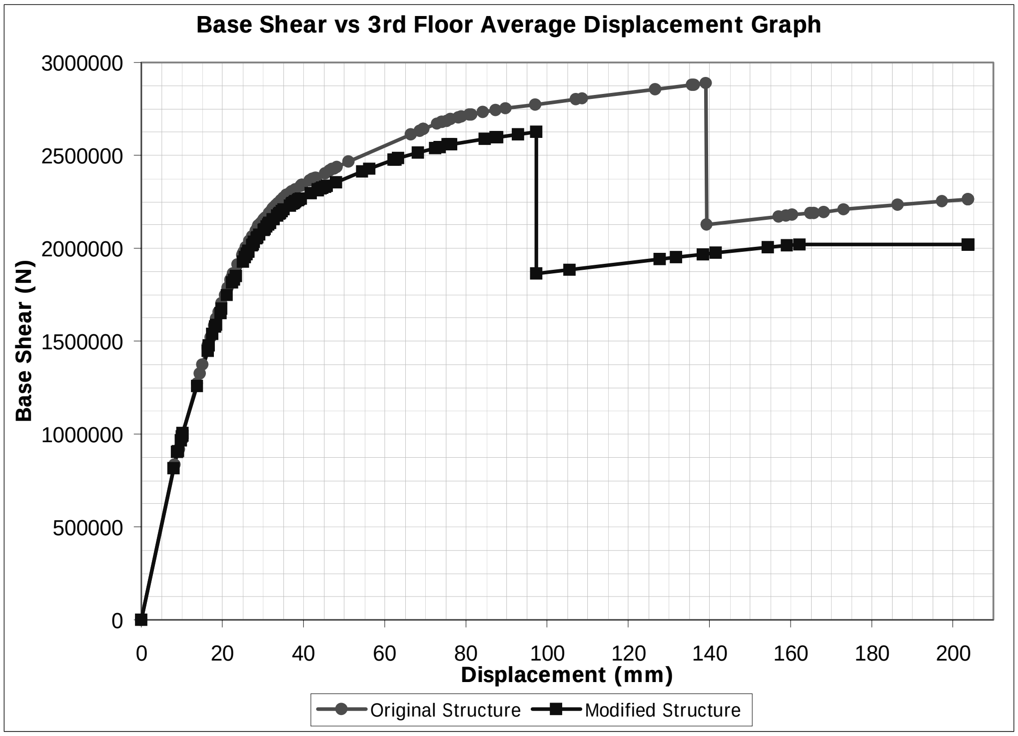

Figure 5.105 (+) X Direction Pushover for Building 4. Removed Member: C0105

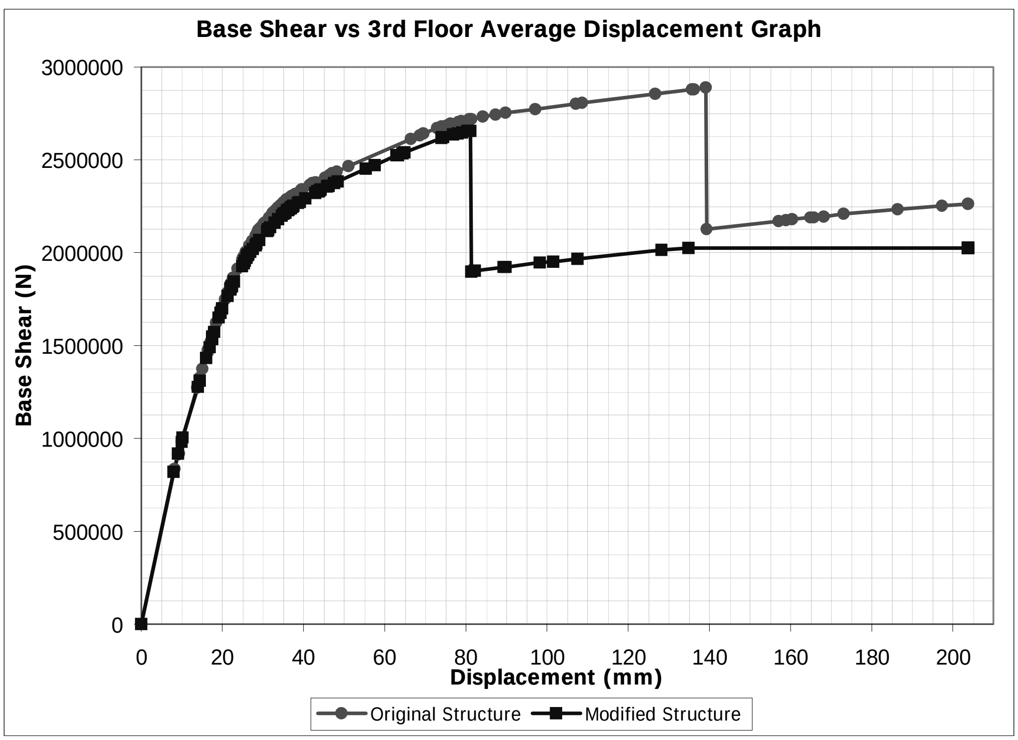

Figure 5.106 (+) X Direction Pushover for Building 4. Removed Member: C0106

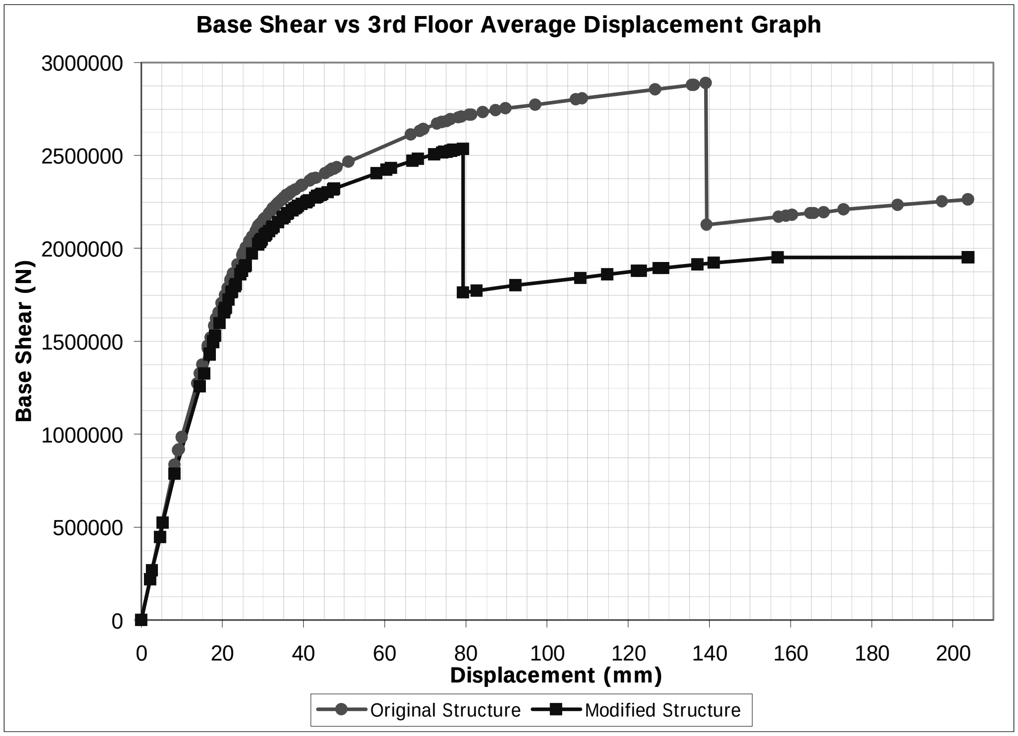

Figure 5.107 (+) X Direction Pushover for Building 4. Removed Member: C0107

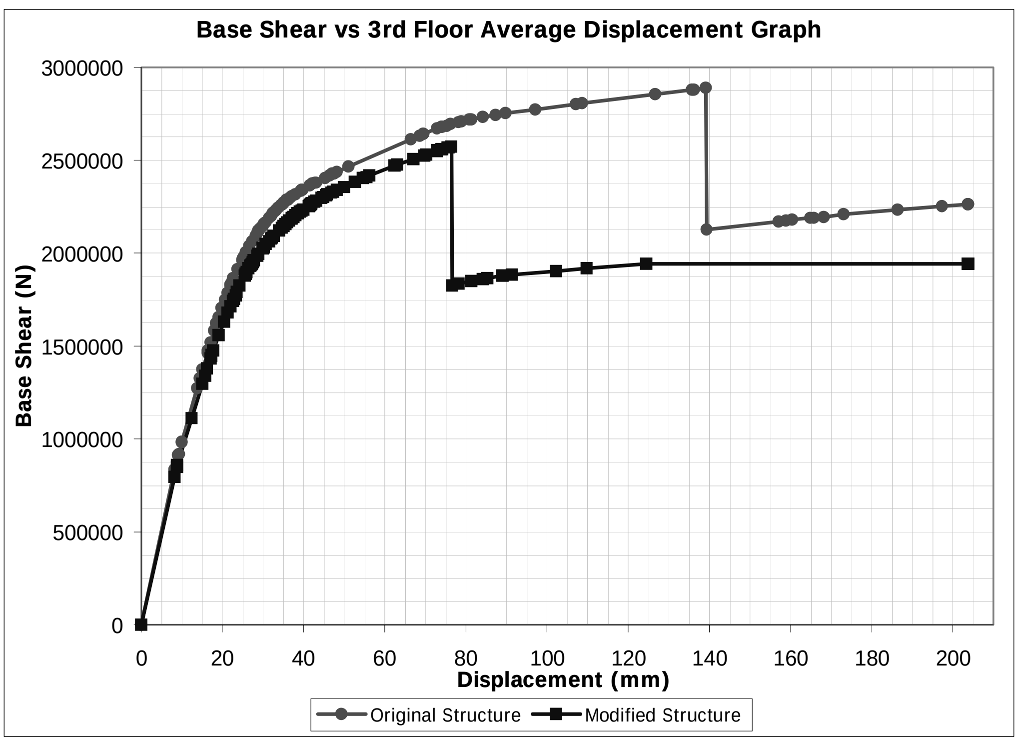

Figure 5.108 (+) X Direction Pushover for Building 4. Removed Member: C0108

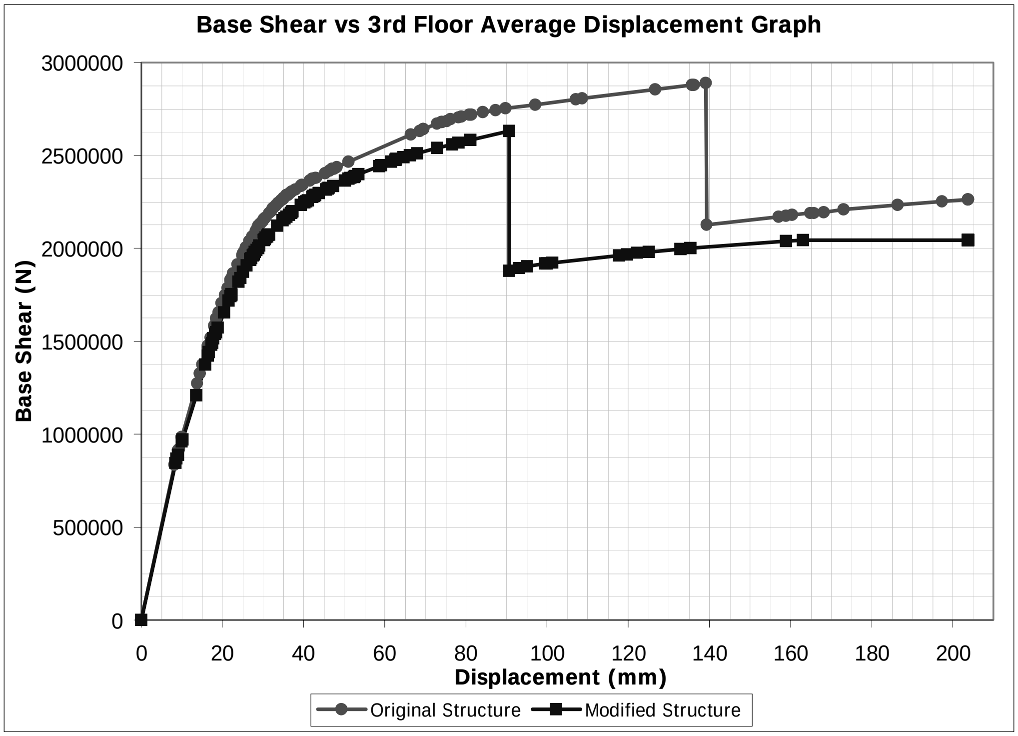

Figure 5.109 (+) X Direction Pushover for Building 4. Removed Member: C0109

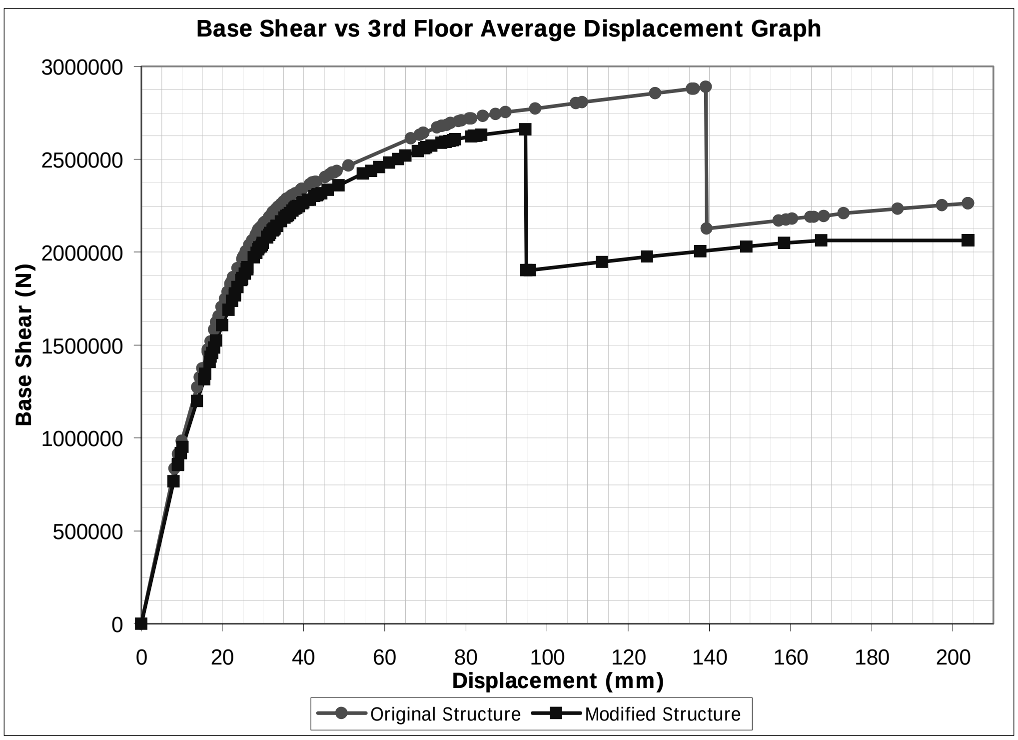

Figure 5.110 (+) X Direction Pushover for Building 4. Removed Member: C0110

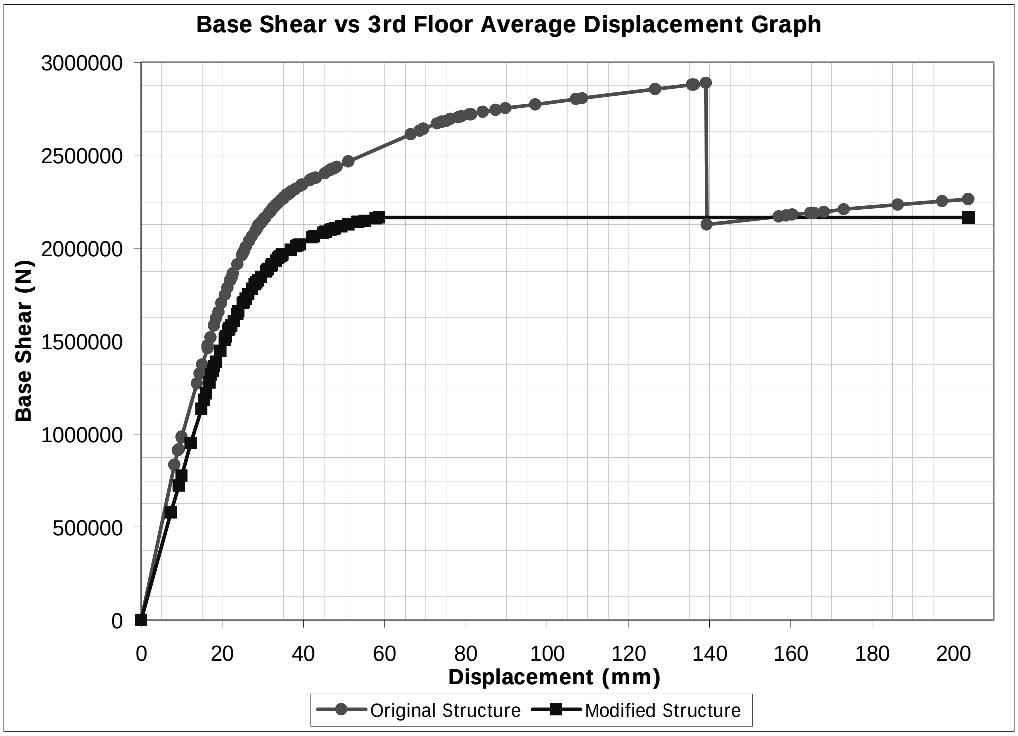

Figure 5.111 (+) X Direction Pushover for Building 4. Removed Member: SW0101

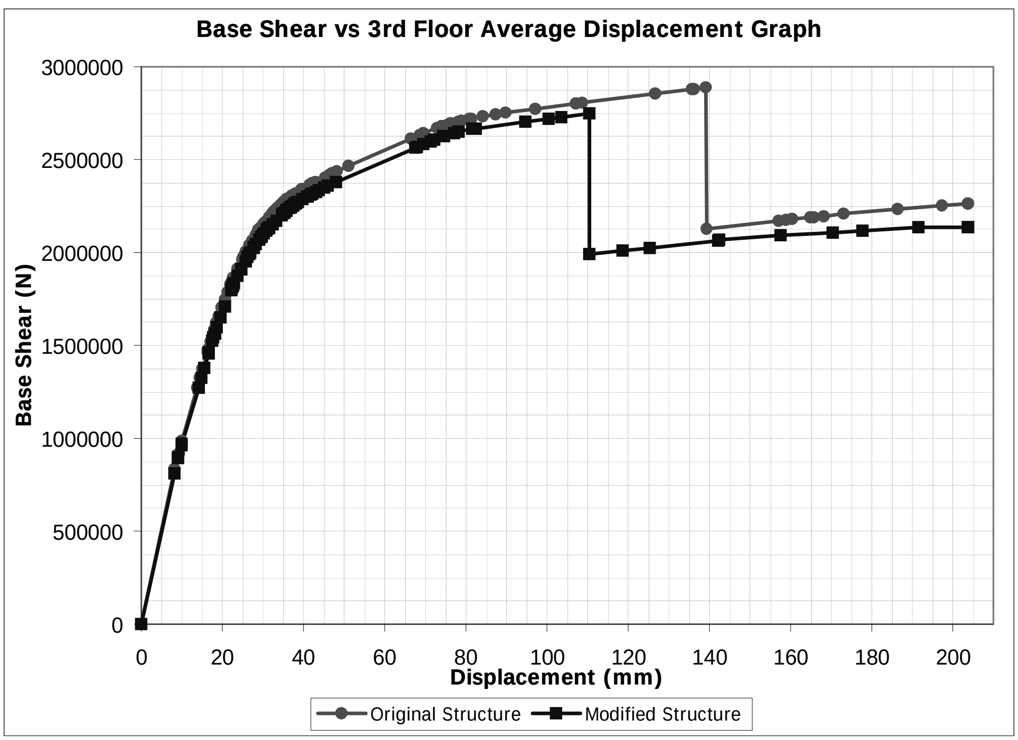

Figure 5.112 (+) X Direction Pushover for Building 4. Removed Member: SW0102

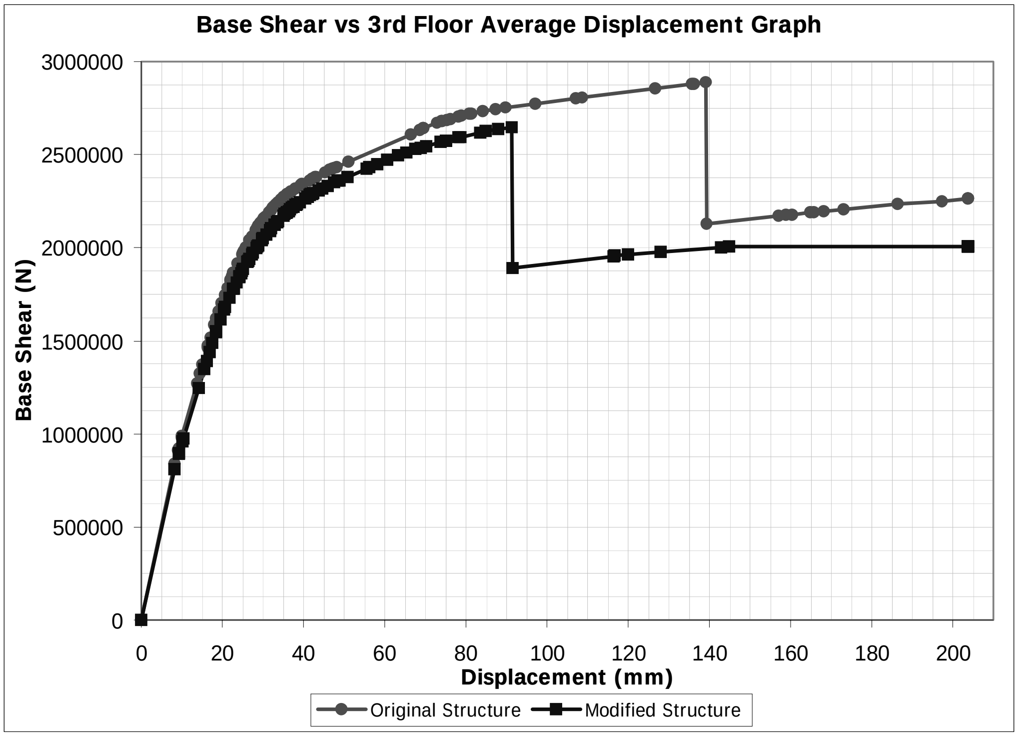

Figure 5.113 (+) X Direction Pushover for Building 4. Removed Member: SW0103

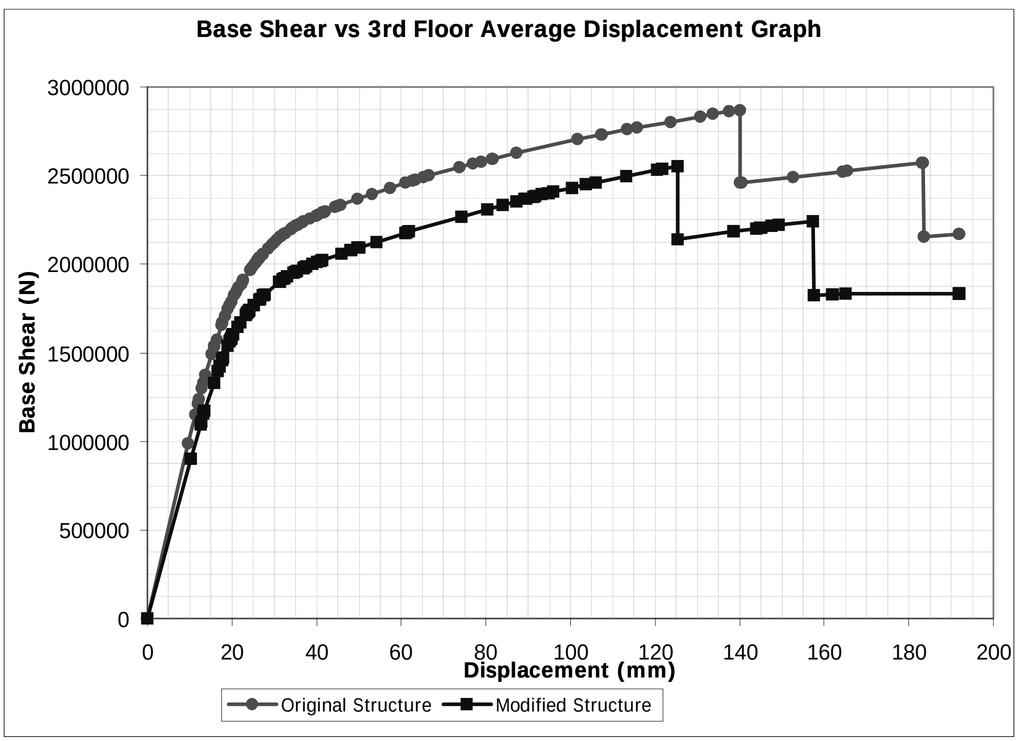

Figure 5.114 (+) Y Direction Pushover for Building 4. Removed Member: C0101

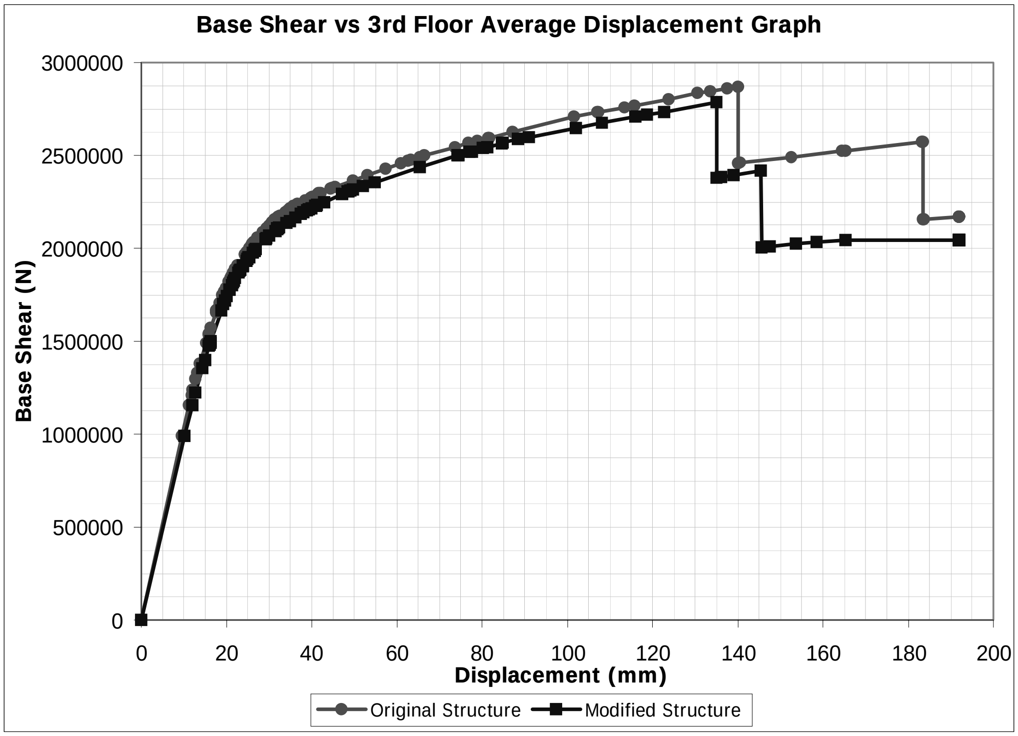

Figure 5.115 (+) Y Direction Pushover for Building 4. Removed Member: C0102

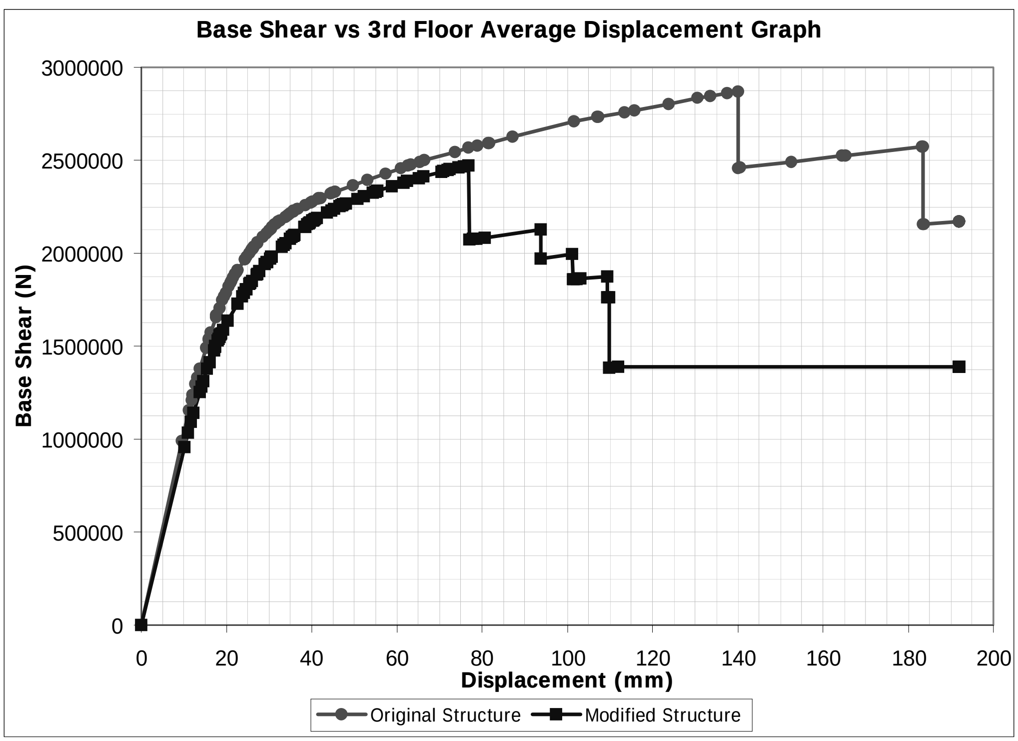

Figure 5.116 (+) Y Direction Pushover for Building 4. Removed Member: C0103

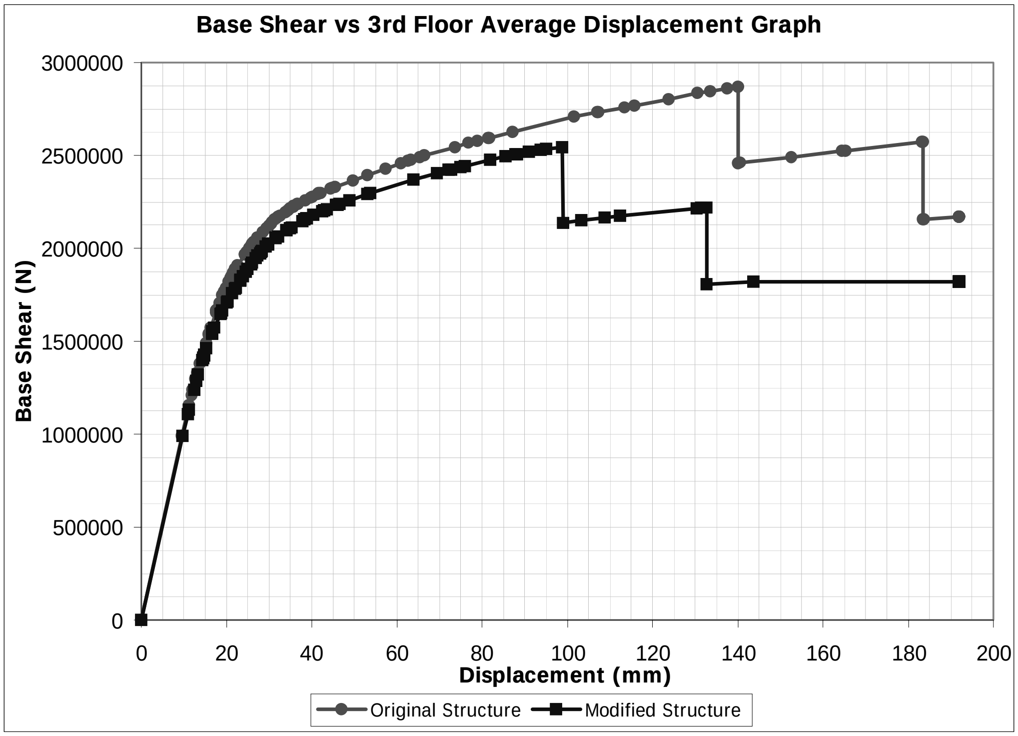

Figure 5.117 (+) Y Direction Pushover for Building 4. Removed Member: C0104

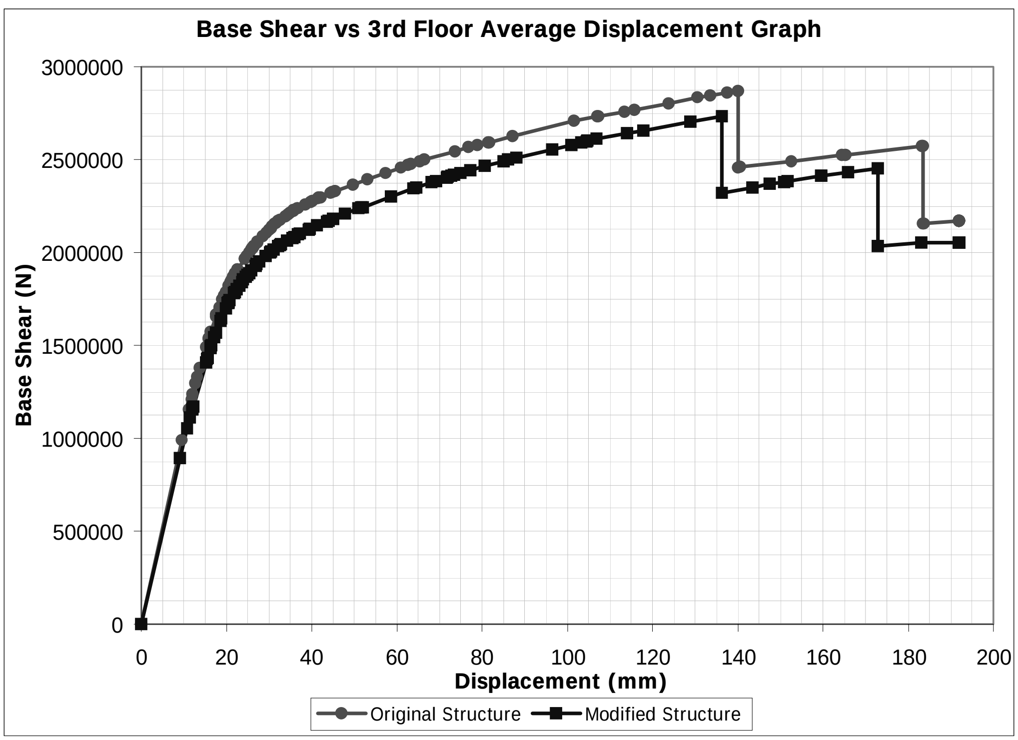

Figure 5.118 (+) Y Direction Pushover for Building 4. Removed Member: C0105

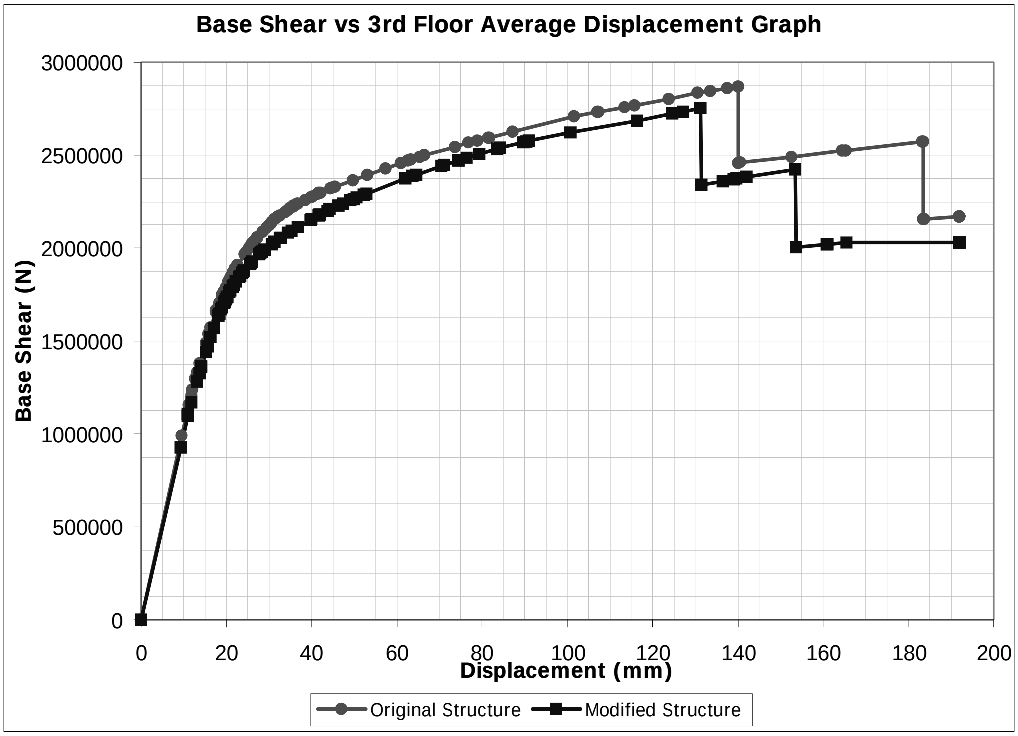

Figure 5.119 (+) Y Direction Pushover for Building 4. Removed Member: C0106

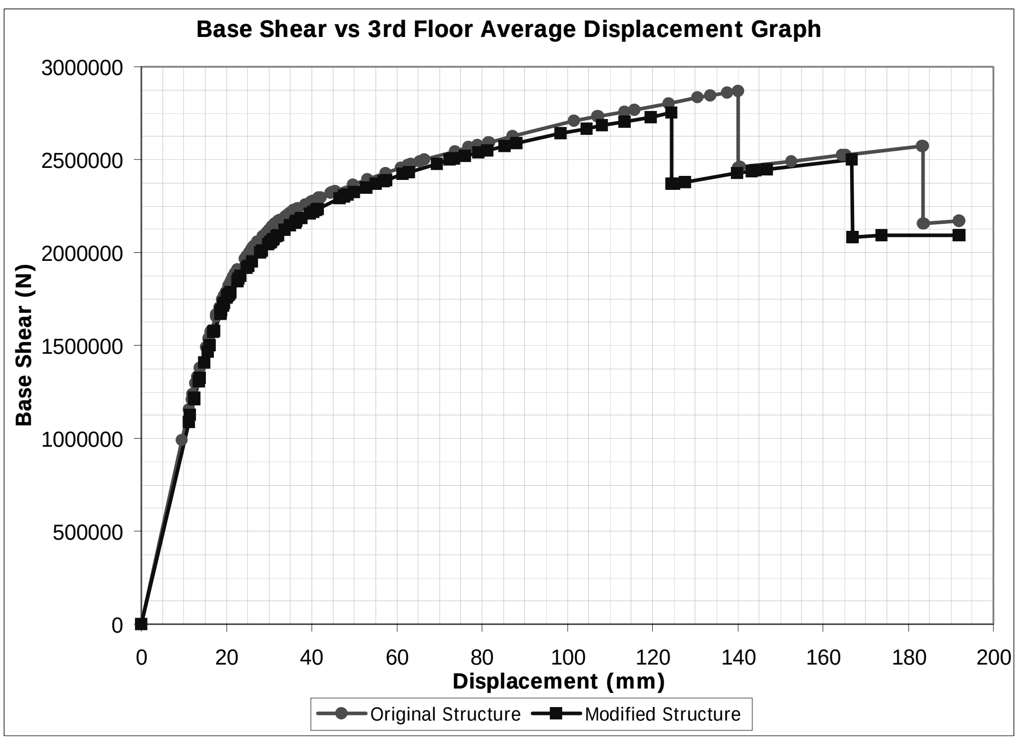

Figure 5.120 (+) Y Direction Pushover for Building 4. Removed Member: C0107

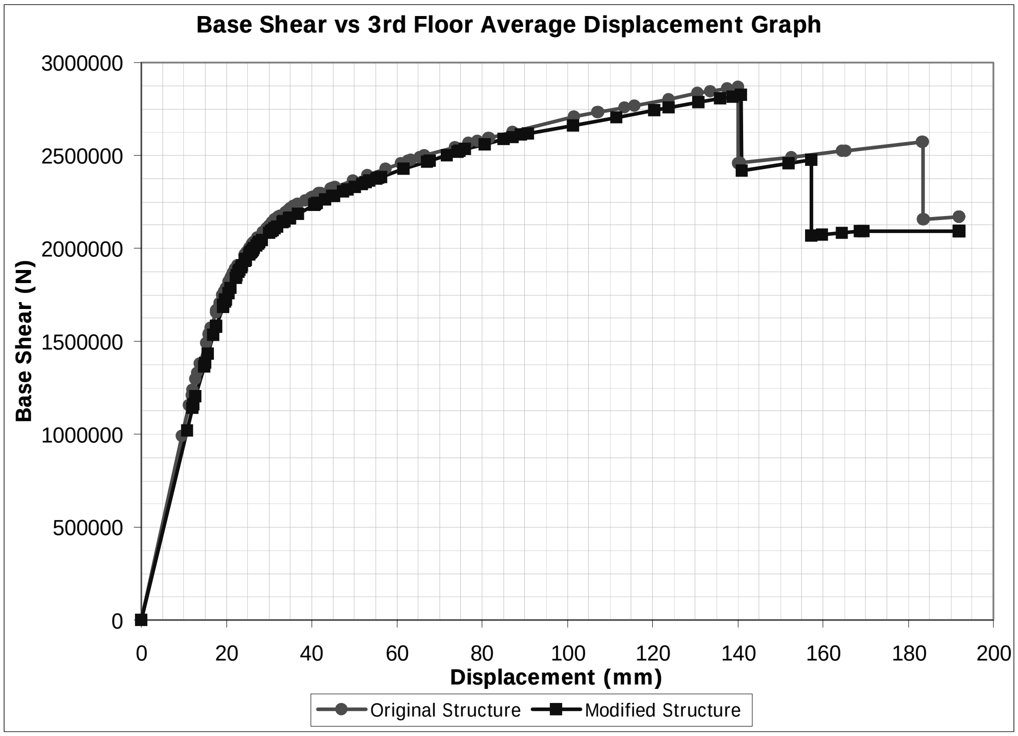

Figure 5.121 (+) Y Direction Pushover for Building 4. Removed Member: C0108

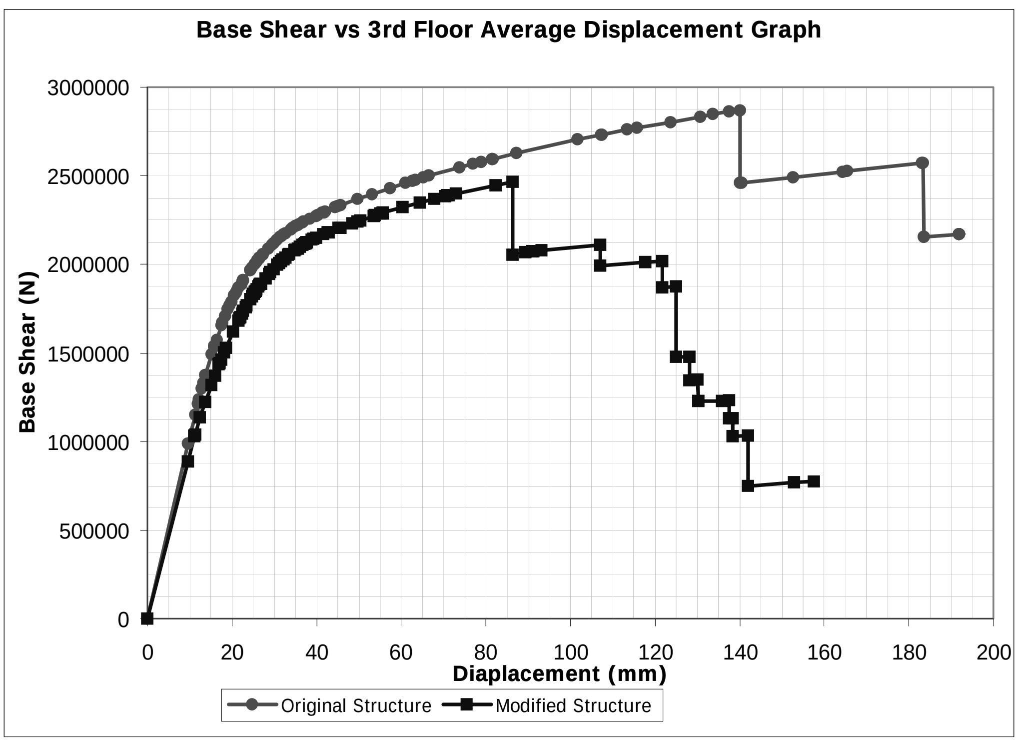

Figure 5.122 (+) Y Direction Pushover for Building 4. Removed Member: C0109

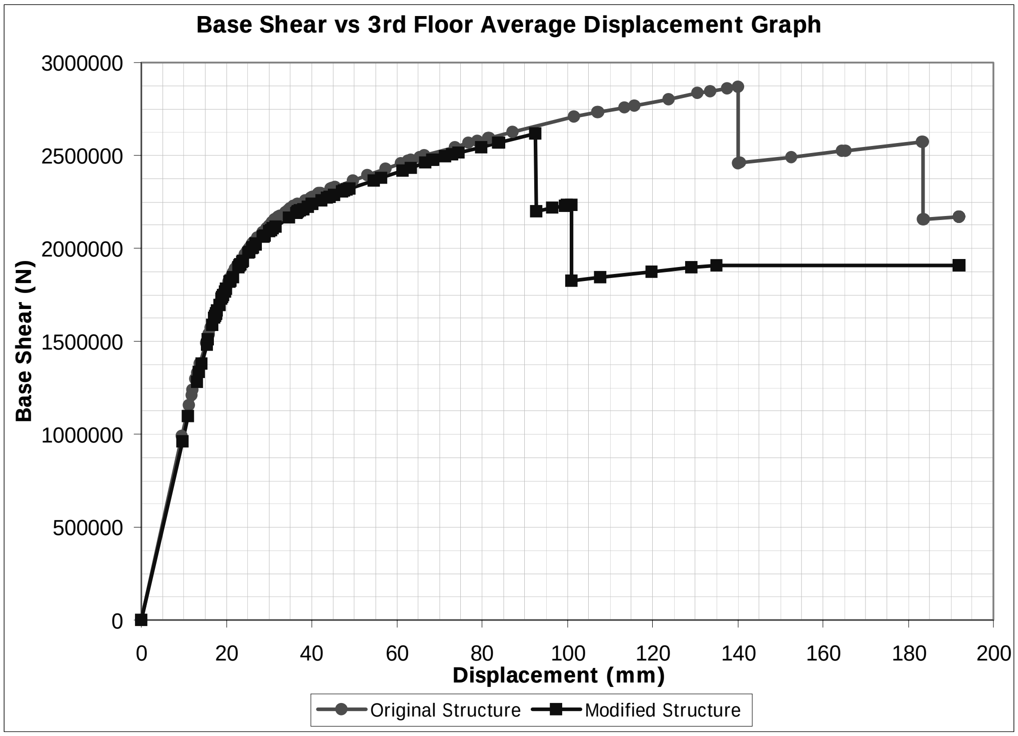

Figure 5.123 (+) Y Direction Pushover for Building 4. Removed Member: C0110

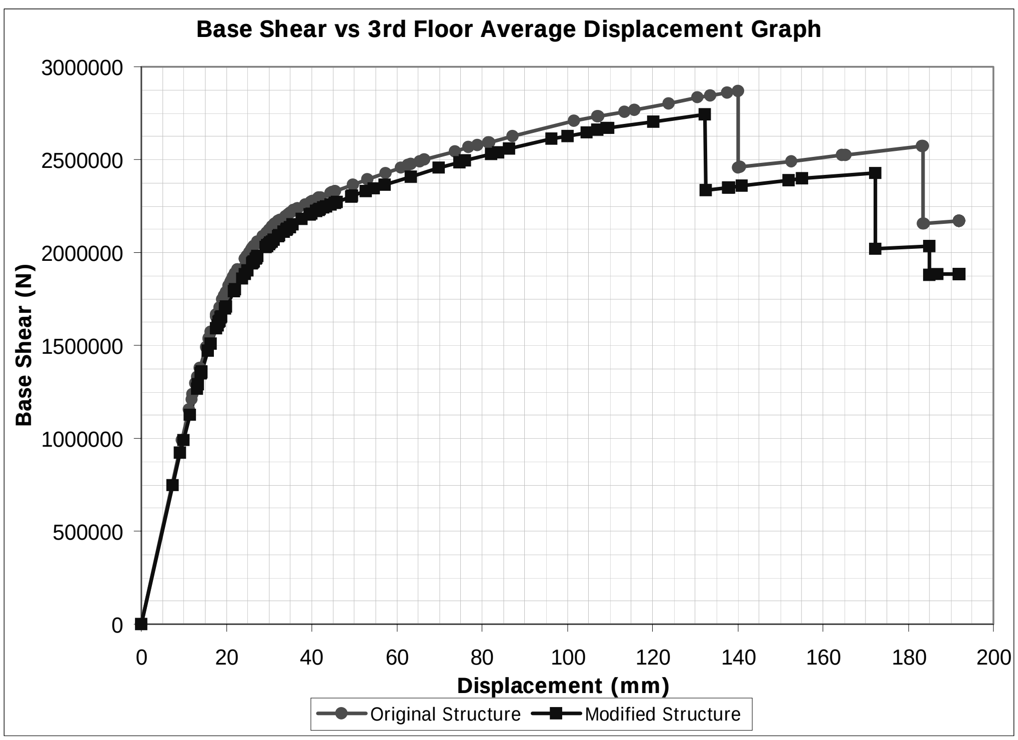

Figure 5.124 (+) Y Direction Pushover for Building 4. Removed Member: SW0101

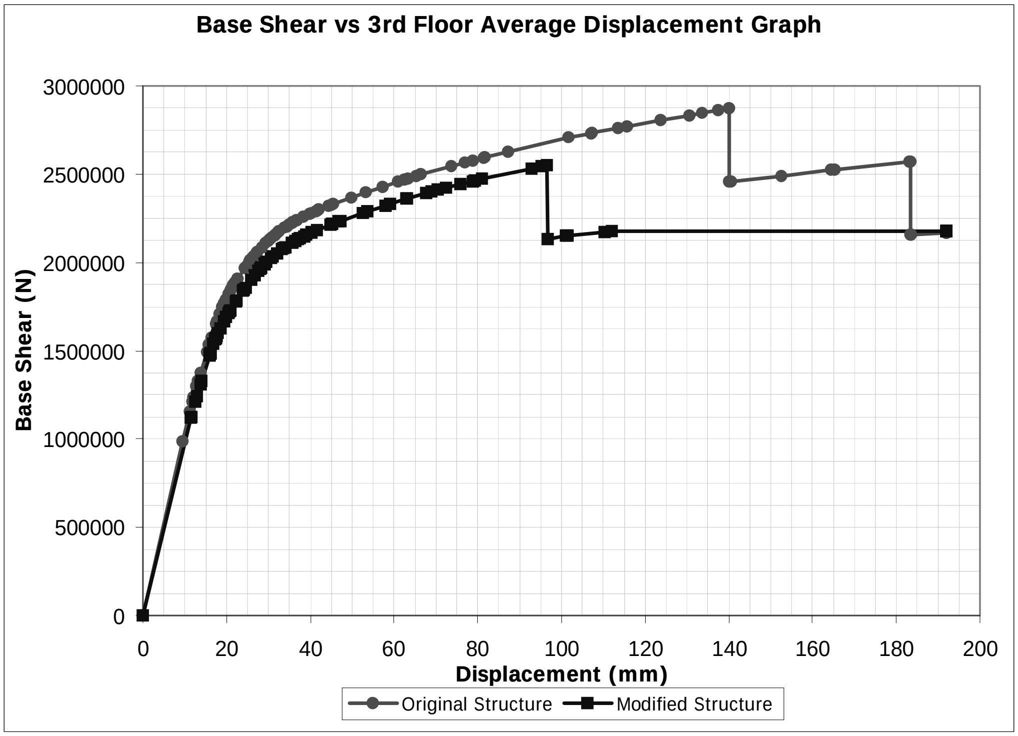

Figure 5.125 (+) Y Direction Pushover for Building 4. Removed Member: SW0102

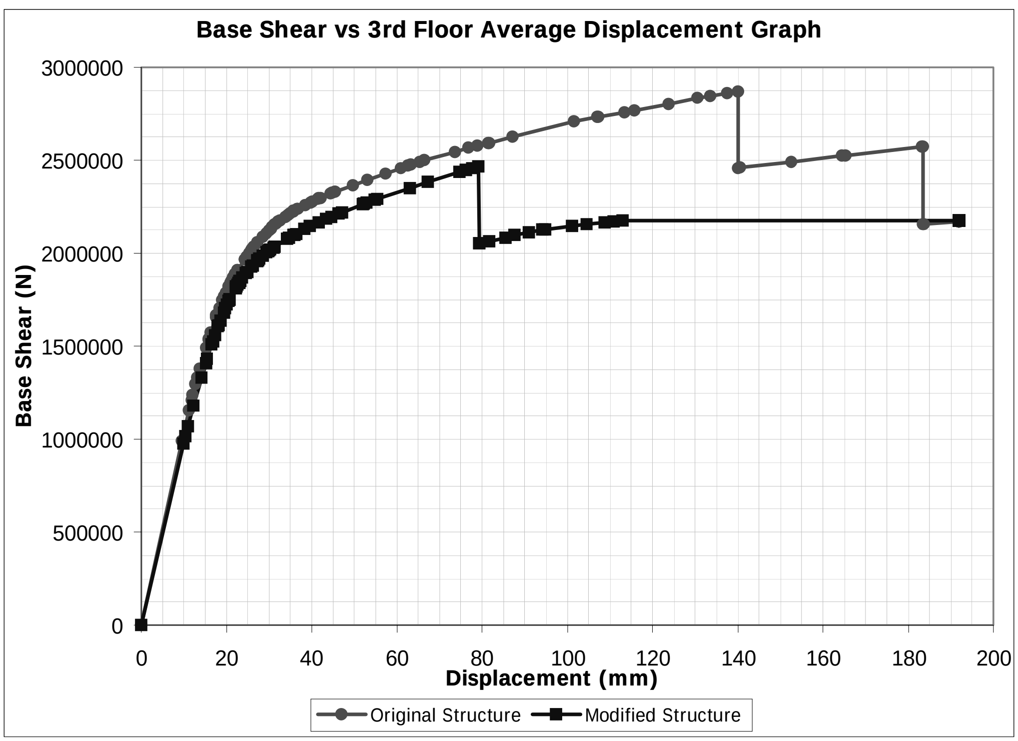

Figure 5.126 (+) Y Direction Pushover for Building 4. Removed Member: SW0103

Discussion of the Results

After pushover analyses are conducted in both directions, importance factors are determined with the methodology described in section 2.2.3.5. Determined Importance Factors for all base members are displayed in Table 5.10 for elastic and plastic approaches.

Table 5.10 Importance Factors for Elastic and Plastic Approaches

	Importance Factors			
	Elastic Approach		Plastic Approach	
Member	X Direction (EX)	Y Direction (EY)	X Direction (PX)	Y Direction (PY)
C0101	-0.011	0.144	0.041	0.147
C0102	-0.011	0.060	0.130	0.066
C0103	0.011	0.085	0.083	0.283
C0104	-0.002	0.020	0.055	0.155
C0105	-0.011	0.055	0.124	0.061
C0106	-0.009	0.028	0.134	0.072
C0107	0.021	0.053	0.174	0.049
C0108	0.030	0.082	0.169	0.042
C0109	0.020	0.097	0.130	0.388
C0110	0.046	0.032	0.119	0.158
SW0101	0.224	0.014	0.140	0.053
SW0102	0.012	0.053	0.075	0.112
SW0103	0.030	0.053	0.131	0.130

The ratio of importance factors obtained by plastic approach to importance factors obtained by elastic approach are presented in Table 5.11.

Table 5.11 Importance Factor Comparison for Elastic and Plastic Approaches

Importance Factor Comparison		
Member	**X Direction**	**Y Direction**
C0101	-382%	102%
C0102	-1158%	110%
C0103	735%	332%
C0104	-3393%	771%
C0105	-1171%	111%
C0106	-1545%	258%
C0107	840%	93%
C0108	557%	51%
C0109	656%	400%
C0110	258%	499%
SW0101	62%	382%
SW0102	618%	211%
SW0103	444%	244%

Discrepancy in the results shown in table 5.11 indicates that the plastic and elastic approaches are not substitute of each other.

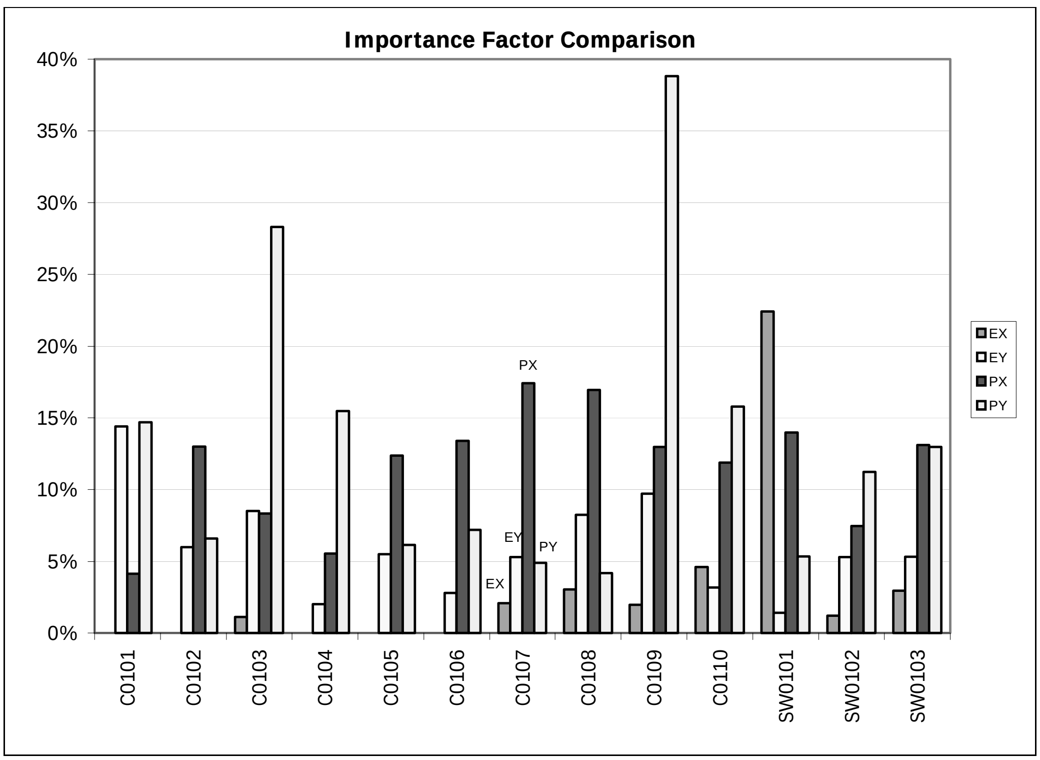

Figure 5.127 Member Importance Factors for Building 4

As pushover curves demonstrate, building shows ductile behavior in both directions. Because both direction dominant mode shape follow translational path as displayed in Figure 5.99 and 5.100. As the displacement is increased, shear wall failures take place. On pushover curves the broken lines (sudden drops on the curve) show the displacements where the shear walls fail. The linear parts of the curve until the shear wall failures indicate that columns are yielded already. After the failure of shear walls total base shear increments gets lower, because there is no member in the system to resist shear forces due to failures and plastic hinge formations. The analysis is stopped at displacement value of approximately 200mm. In X direction as soon as the shear wall SW0101 fails, building displaces some more because at this displacement there exist some columns which are not yielded yet.

When the figures are examined, the important members in both directions are observed as the ones which are located in the corresponding direction. The members with strong axis parallel to the excitation direction resist mainly to the applied shear forces. When the pushover is conducted in Y direction, the importance factors are distributed almost equally over the structure as seen in Figure 5.127. Where as in X direction the high importance factors are distributed on the edges of the of the building.

Figures 5.128 and 5.129 display the distribution of importance factors along members in X and Y directions, respectively. In the graph it is observed that high importance ratios are distributed along different members due distribution of the columns on the layout.

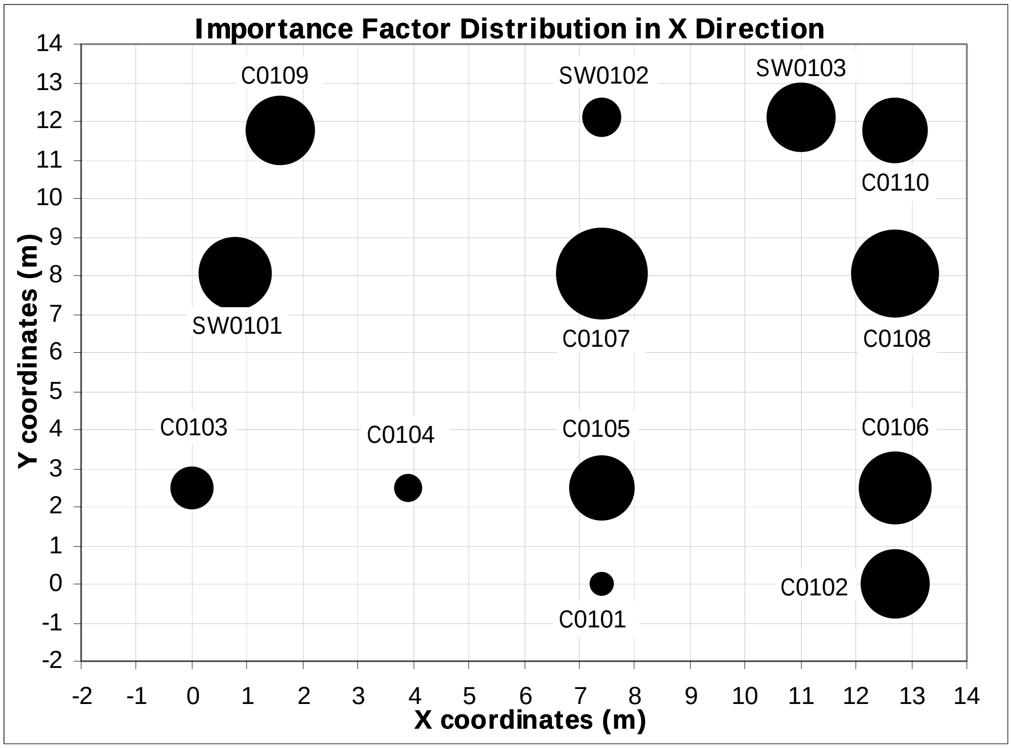

Figure 5.128 Importance Factor Distirbution in X Direction for Building 4

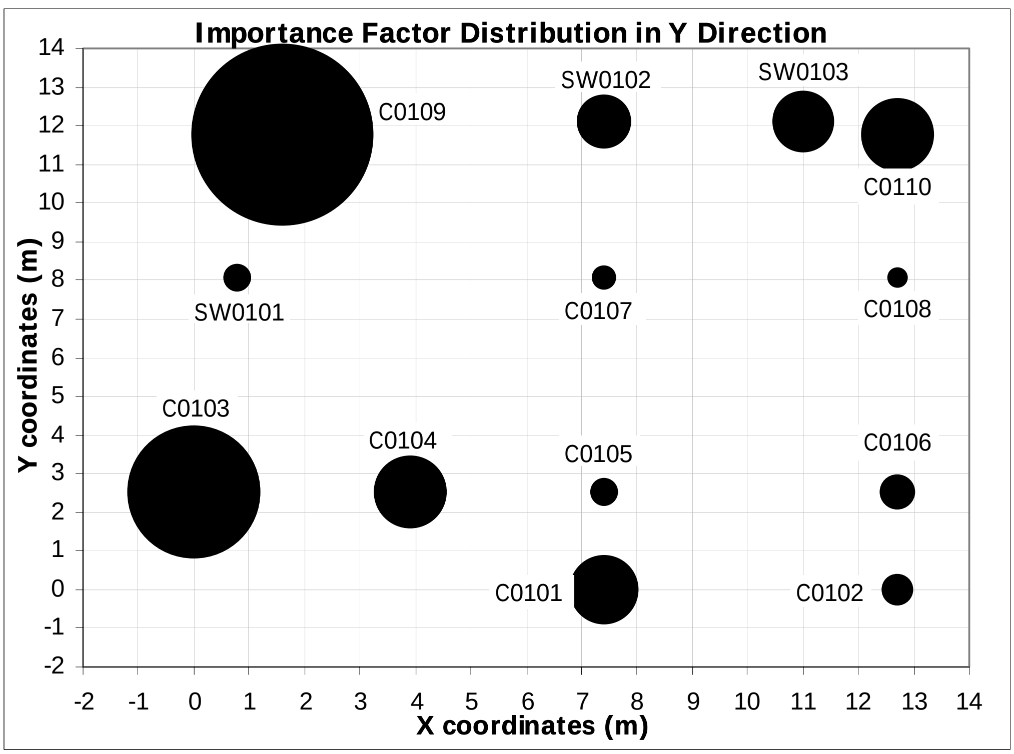

Figure 5.129 Importance Factor Distirbution in Y Direction for Building 4

5.3.5 Discussion On Pushover Displacement Increments

During evaluation of above defined 4 buildings, pushover analyses are conducted with 0.1 mm increments. To determine the degree of sensitivity of the analyses with respect to the introduced increments, in X direction additional six pushover analyses are conducted for Building 1 with various increments. In all analyses column C0103 is removed and importance factor is computed. For increments of 0.05mm, 0.1mm, 0.2mm , 0.5mm, 1.0mm, 2.0mm and 5.0mm , calculated importance factors of column C0103 is displayed in Table 5.12.

Table 5.12 Relation between Refinement and Importance Factors

Relation between Refinement and Importance Factors	
Push Increment (mm)	Computed Importance
0.05	0.098
0.1	0.098
0.2	0.099
0.5	0.096
1.0	0.102
2.0	0.103
5.0	0.095

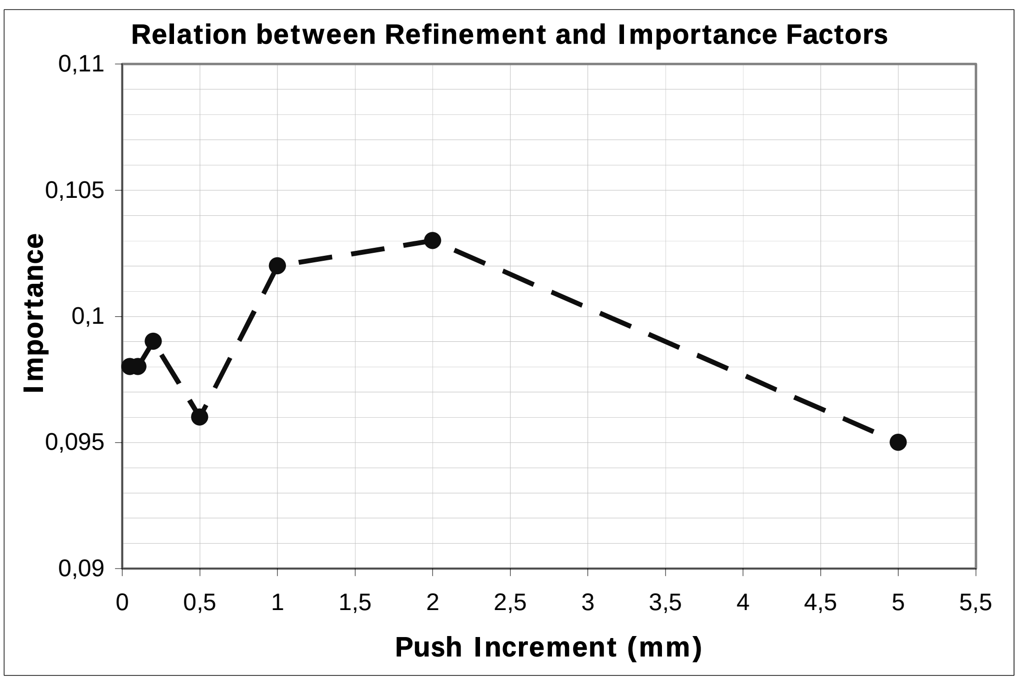

Figure 5.130 Relation between Refinement and Importance Factors

Table 5.12 and Figure 5.130 show the convergance of the analyses for the push increments smaller than 1mm. There is possibility to get unexpected results for the increments greater than 1mm. Although analyses process takes longer time for the increments smaller than 1mm. In this study it is suggested to use incremtents smaller than 1mm to get optimum results.

5.3.6 Beam Importance Factor Evaluation

In this study, beam importance concept is also studied. Same procedures that is applied to columns and shear walls are applied to beams also. To demonstrate the contribution of the beams to the energy dissipation capacity of the building, evaluation procedure is applied to the Building 4 defined in section 5.3.4 and calculated importance factors for plastic approach are presented in Table 5.13**.** Evalutaion is conducted for four different casses:

1. Beam B0116 is removed from first floor.
   Obtained pushover curves are displayed in Figure 5.131 for X direction and in Figure 5.132 for Y direction.
2. Beam B0118 is removed from first floor.
   Obtained pushover curves are displayed in Figures 5.133 for X direction and in Figures 5.134 for Y direction.
3. All of the first floor beams are removed.
   Obtained pushover curves are displayed in Figures 5.135 for X direction and in Figures 5.136 for Y direction.
4. All the beams are removed .
   Obtained pushover curves are displayed in Figures 5.137 for X direction and in Figures 5.138 for Y direction.

Table 5.13 Beam Importance Factors for Plastic Approach

	Importance Factors for Plastic Approach	
Member	**X Direction**	**Y Direction**
B0116	0.011	-0.001
B0118	0.001	-0.020
First Floor Beams	0.069	0.111
All Beams	0.217	0.370

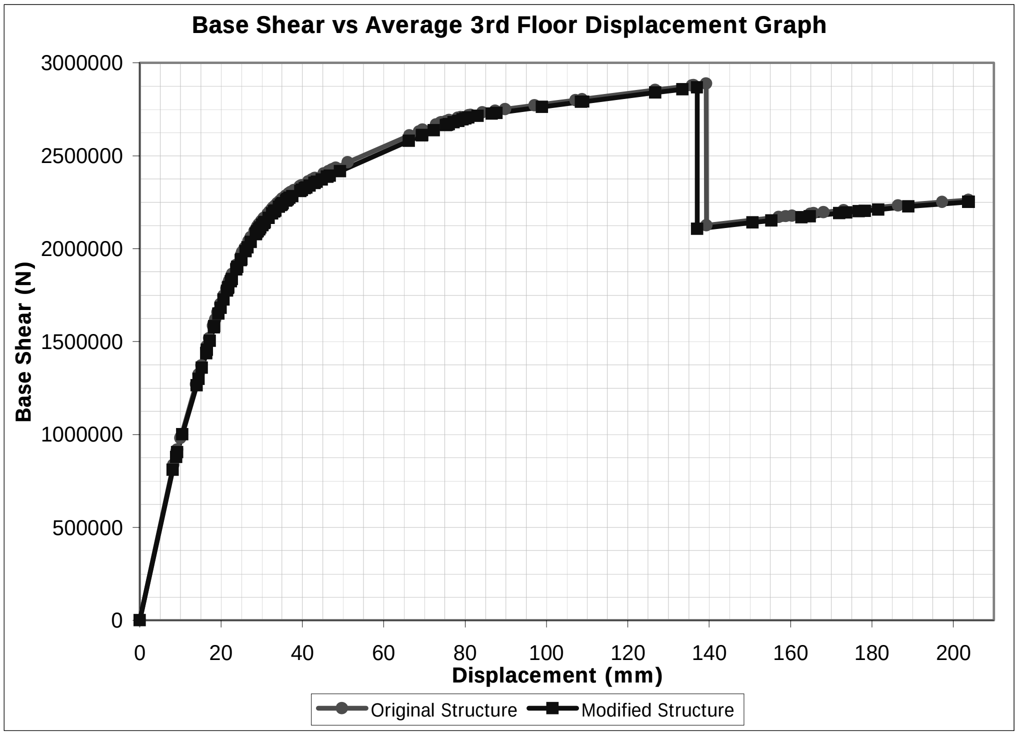

Figure 5.131 (+) X Direction Pushover for Building 4. Removed Member: B0116

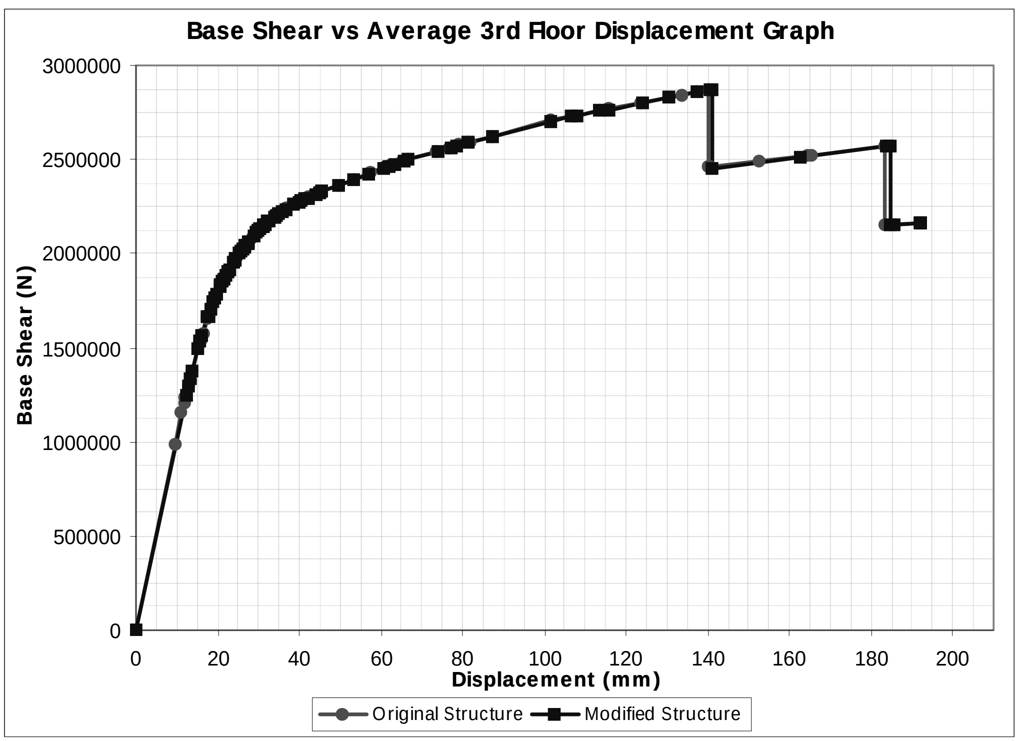

Figure 5.132 (+) Y Direction Pushover for Building 4. Removed Member: B0116

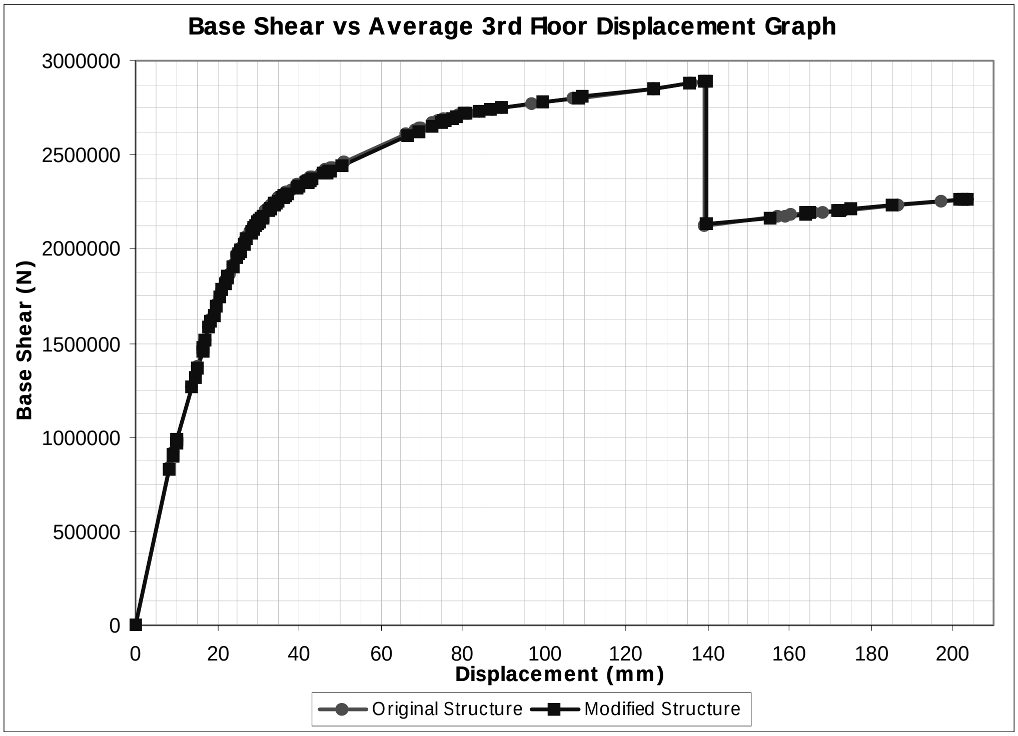

Figure 5.133 (+) X Direction Pushover for Building 4. Removed Member: B0118

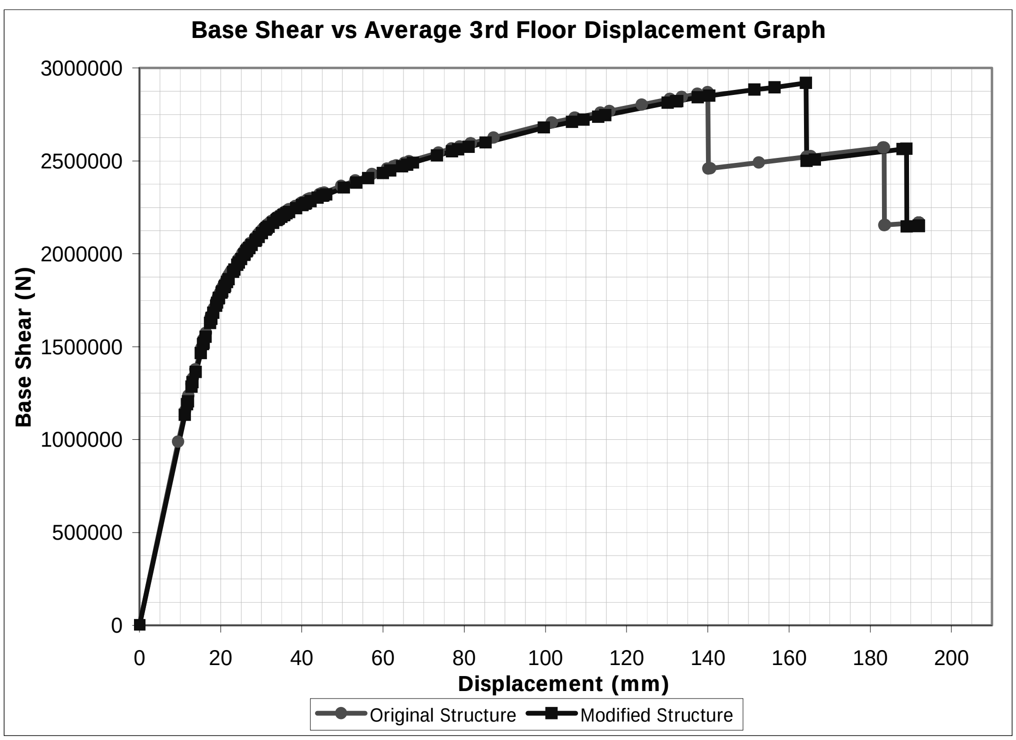

Figure 5.134 (+) Y Direction Pushover for Building 4. Removed Member: B0118

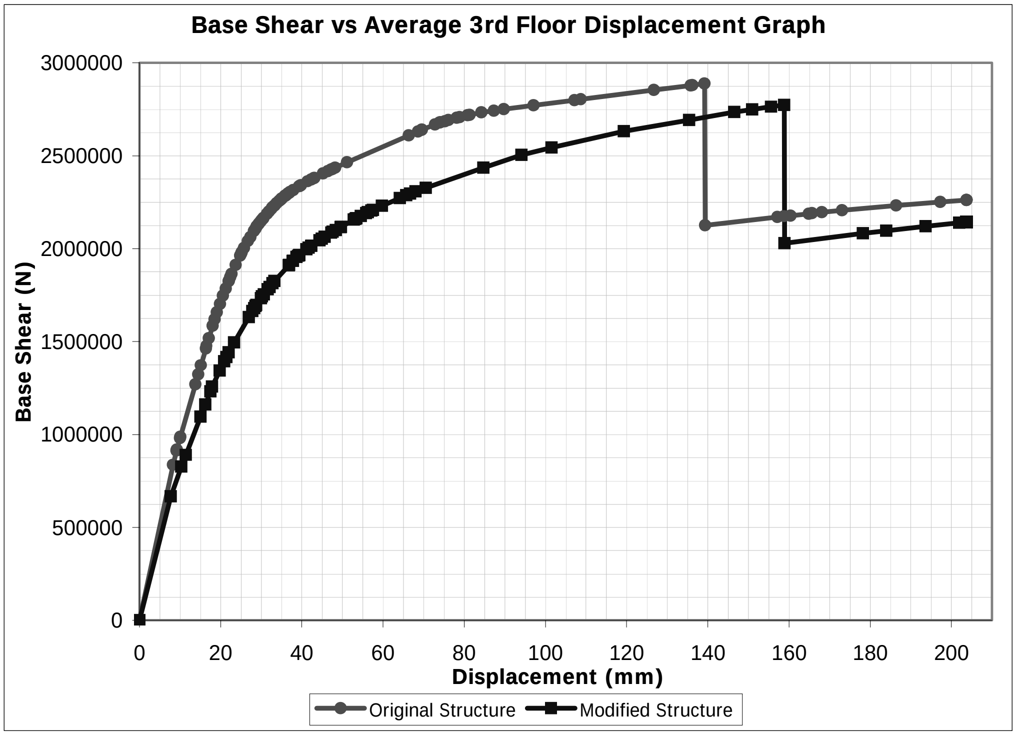

Figure 5.135 (+) X Direction Pushover for Building 4.All First Floor Beams are removed

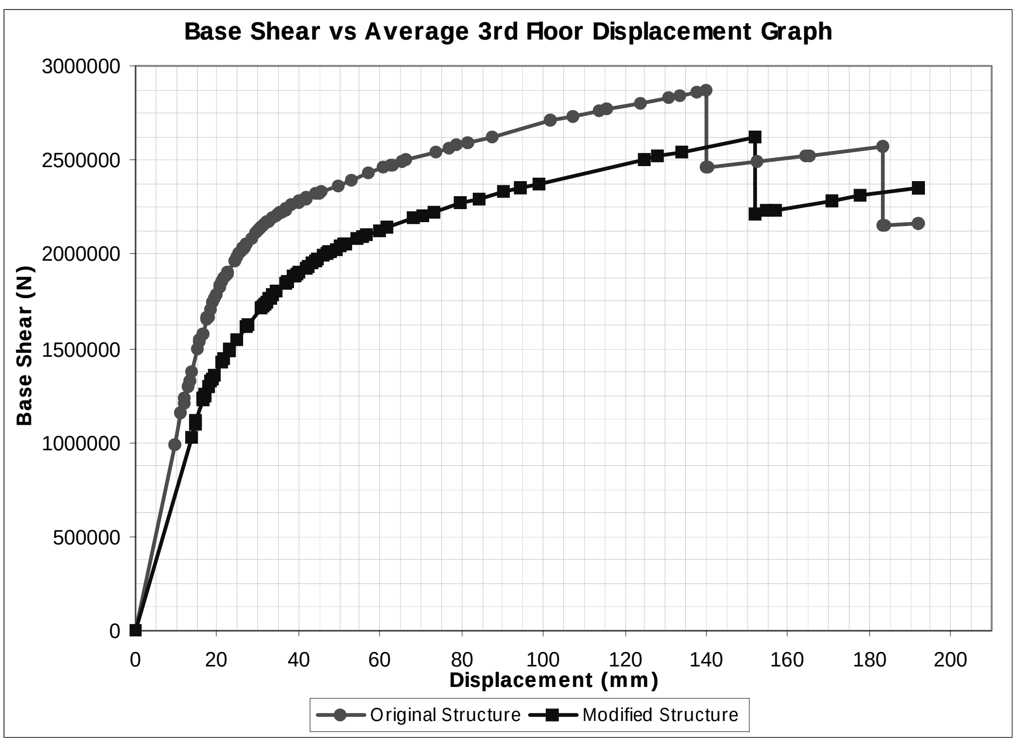

Figure 5.136 (+) Y Direction Pushover for Building 4.All First Floor Beams are removed

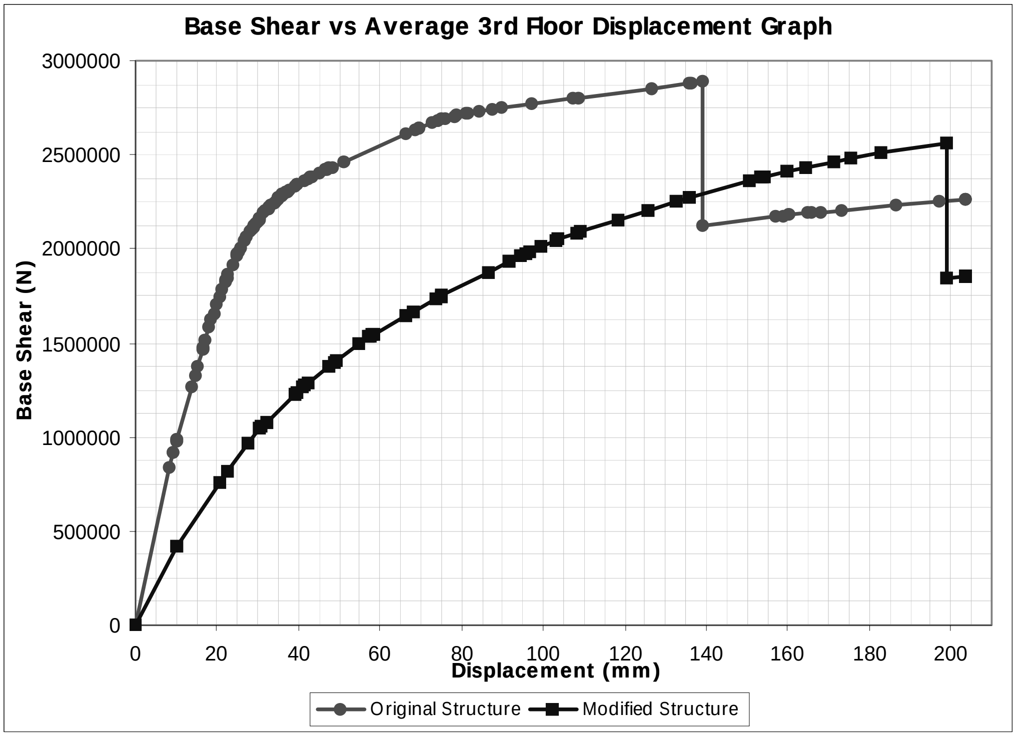

Figure 5.137 (+) X Direction Pushover for Building 4.All Floor Beams are removed

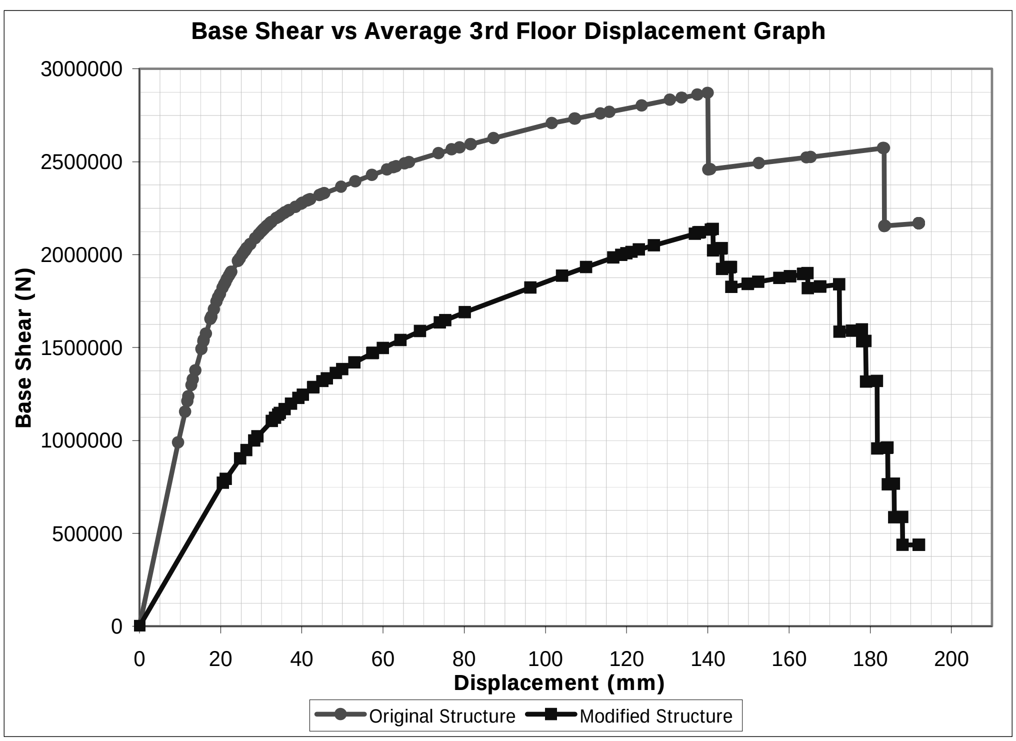

Figure 5.138 (+) Y Direction Pushover for Building 4.All Floor Beams are removed

Discussion of Results

The importance factors presented in Table 5.12 indicate that the contribution of single beam to the energy dissipation capacity of the building is insignificant. Also for beams B0116 and B0118 negative importance in Y direction is observed. This negative importance is due to delay in failure of shear wall when compared with the original building. But, when first floor beams are studied, reltively high importance is observed, becuse removing all the beams from first floor reduces stiffness of the building as seen in Figures 5.135 and 5.136. To see the affect of all the beams on the beahvior of the building, all the beams are removed from the structure and analyses conducted. In this case stiffness of the building reduces considerably as seen in Figures 5.137 and 5.138. As expected importance calaculated is relatively high.

These analyses show the contribution of beams to the buillding behavior. In building vulnerability index calculations beams should also be included to get more realistic results. The detailed analyses including beam contribution are planned as future study.

CHAPTER 6

SESISMIC VULNERABILITY INDEX COMPUTATION PROCEDURE

6.1 INTRODUCTION

Two main objectives of this study are:

1. To develop a method to compute member importance factors in R/C buildings, using nonlinear analyses.
2. To develop a method to compute of seismic vulnerability index of R/C buildings, using member importance factors.

In this chapter details of proposed method for vulnerability index computation procedure are presented.

6.2 VULNERABILITY INDEX COMPUTATION PROCEDURE

Two main attributes are used during computation of vulnerability index of the buildings. These are as follows:

1. Capacity usage (U_m) of the members. This property indicates the ratio of applied loads to the capacity of the member.
2. Importance (I_m) of the members.

Vulnerability of a member is computed based on above-mentioned items as follows:

$$V_m = I_m \cdot U_m \qquad (6.1)$$

Member vulnerability (V_m) is a measure that determines the relative effect of each member on the overall vulnerability of a building.

Capacity usage (U_m) of a member is determined by using the results of spectrum analyses. Spectrum analyses are performed in X and Y directions to determine member forces. In both x and y directions, member forces are compared with the capacities of sections. Capacity usages of the members are calculated by taking ratio of applied laods to member capacity.

Member importance factors (I_m) are determined for both directions using nonlinear analyses. This procedure is explained in Chapter 5.

The weighted average of capacity usages (U_m) using member importance factors (I_m) determines the *building vulnerability index (S_v)* as shown in Equation 6.2. The building vulnerability index (S_v) is also equal to ratio of total member vulnerabilities (V_m) to the summation of member importance factors (I_m).

$$S_v = \frac{\sum (I_m \cdot U_d)}{\sum I_m} = \frac{\sum V_m}{\sum I_m} \qquad (6.2)$$

The obtained vulnerability index "S_v" will be evaluated using pre-determined vulnerability index intervals in order to decide on the expected damage level of a building. Determination of vulnerability index limits is out of the scope of this study, but planned as a future study.

The advantage of the proposed seismic vulnerability index computation method is that the method combines structural non-linear response of a building on a member scale, with general design concepts to calculate a unique building vulnerability index, which can be further used to estimate the building performance level building as a future study.

6.3 VULNERABILITY INDEX COMPUTATION PROCEDURE APPLICATION

The application of the proposed method is demonstrated using the building model defined in section 5.3.1.

The steps followed are briefly explained below:

1. Design spectrum analyses are conducted on the structure in both x and y directions using the proposed spectra in the current earthquake code.
2. To determine member capacity usage levels (U_m) in both directions, member forces which are obtained after the analyses are compared with the capacity of the members for combination of axial load & moment and torsion & shear forces. The obtained usages of the members are demonstrated in Tables 6.1 and 6.2.

Table 6.1 Capacity Usages in X direction

Capacity Usages in X direction		
T-V2	**T-V3**	**P-M-M**
0.13	0.10	0.49
0.15	0.10	0.45
0.14	0.10	0.47
0.14	0.11	0.55
0.16	0.09	0.51
0.11	0.13	0.47
0.17	0.10	0.67
0.17	0.10	0.61
0.17	0.10	0.63

Table 6.2 Capacity Usages in Y direction

Capacity Usages in Y direction		
T-V2	**T-V3**	**P-M-M**
0.06	0.11	0.46
0.07	0.13	0.49
0.07	0.13	0.57
0.06	0.12	0.49
0.07	0.14	0.50
0.14	0.07	0.59
0.07	0.11	0.47
0.07	0.12	0.46
0.07	0.13	0.57

3. Pushover analyses are performed in both directions for the original building by using CAVAS.
4. Base floor columns are removed from the building one by one, and a separate pushover analysis is conducted using CAVAS for each newly generated building model missing a column.
5. Member importance factors are determined using the procedure explained in section 5.3. The calculated member importance factors are shown in Table 6.3

Table 6.3 Importance Factors for the building

	Importance Factors	
	Plastic Approach	
Member	**X Direction**	**Y Direction**
C0101	0.021	0.069
C0102	0.000	0.066
C0103	0.023	0.114
C0104	0.106	0.066
C0105	0.066	0.098
C0106	0.056	0.163
C0107	0.254	0.113
C0108	0.172	0.137
C0109	0.386	0.239
Sum:	**1.084**	**1.066**

6. In both directions, importance factor of each member is multiplied with the corresponding max capacity usage to determine member vulnerability (V_m). The V_m values for all members are calculated and shown in Table 6.4 for both directions.

Table 6.4 Vulnerability of Members

	Member Vulnerability	
Member	**In X direction**	**In Y direction**
C0101	0.010	0.032
C0102	0.000	0.032
C0103	0.011	0.065
C0104	0.058	0.033
C0105	0.034	0.049
C0106	0.026	0.096
C0107	0.170	0.053
C0107	0.105	0.063
C0109	0.243	0.136
Sum:	**0.658**	**0.560**

Using formulation 6.2 building vulnerability indices in both directions are computed as follows:

$$S_{vx} = \frac{\sum V_m}{\sum I_m} = \frac{0.658}{1.084} = 0.607 \text{ in X direction.} \quad (6.3)$$

$$S_{vy} = \frac{\sum V_m}{\sum I_m} = \frac{0.560}{1.066} = 0.525 \text{ in Y direction.} \quad (6.4)$$

7. The building vulnerability index (S_v) is calculated as the summation of the maximum and 30% of the minimum vulnerability indices in x and y directions.

$$S_v = \max(S_{vx}, S_{vy}) + \alpha_v \cdot \min(S_{vx}, S_{vy}) \quad (6.5)$$

$$S_v = 0.607 + 0.3 \cdot 0.525 = 0.7645 \quad (6.6)$$

As shown in item 7, it is proposed to take the value of $\alpha_v = 0.3$.

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 SUMMARY

In this study, software named "CAVAS" (Computer Aided Vulnerability Assessment Software) is developed, which is mainly used to calculate member importance factors and conduct building vulnerability index based on member demand to capacity ratios and calculated member importance factors. CAVAS has the ability to conduct numerous automatic pushover analyses as it removes each member from a building, generates pushover curves, and then calculates importance factors of each member.

CAVAS is a powerful engineering tool with the following contributions:

- CAVAS has uncomplicated input file format specially designed for R/C type buildings. By using facilities implemented in CAVAS, numerous three-dimensional (3D) SAP2000 input files are automatically generated.
- Moment-curvature and moment-axial load interaction diagram generation is implemented as a tool inside CAVAS.
- CAVAS has flexible pushover capabilities with following features/options:
  - After the pushover analysis is conducted for the original building, each column and shear wall is automatically removed from the structure and a separate pushover analysis is automatically conducted. The results are post-processed and presented in a chart format by the program.
  - User can choose application direction (x or y) of the pushover analysis.

- Simulation of failure is provided optionally in CAVAS. The possible failure scheme can be determined using this facility.
- There are optional capacity check procedures in CAVAS. Building behavior can be studied for various possibilities by choosing from different application combinations (e.g., ignore shear failure in beams, reduce shear capacity after plastic hinge formation, etc.).

The main steps of automated member importance factor determination procedure carried out by CAVAS are as follows:

1. Pushover analysis is performed initially for the original structure
2. One member (column, shear wall, beam) is removed from the structure
3. Pushover analysis is performed for the modified structure
4. Removed member is placed to its original location.
5. Subsequent member is removed from the structure and Step 3 is repeated until all members are evaluated.
6. Importance of each member is calculated based on the assumption: "Importance of a member is proportional with its contribution to the energy dissipation capacity of a structure"

Each member's capacity demand ratios are calculated using spectrum analysis. The overall building vulnerability index is computed using the member importance factors as weighted average multipliers for the computed member capacity demand ratios.

7.2 CONCLUSIONS

1. The software developed in this study is a tool, which is used to streamline FE Model generation, related analysis, and post-processing work for member importance calculation and building vulnerability index calculation.

2. In this study, non-linear analysis results are used to calculate member importance factors. A simpler method would be using elastic analyses results for calculation of importance factors; however, results show that plastic and elastic approaches give different results and are not substitutes of each other.

3. Proposed method determines member importance factors and calculates vulnerability index using 3D-nonlinear analysis approach: some statistical vulnerability assessment procedures generally use an approach by considering total member (shear wall and/or column) ratio of cross sectional and floor areas as an important parameter. Different buildings might have similar total member and floor area ratios, but structural system layout, collapse mechanisms and as a result, the seismic vulnerability may be completely different. Linear versus non-linear behavior and location of a member affecting its importance in a three-dimensional sense are important issues, which are included in this study.

4. The proposed method enables determination of member importance factors specific to each different building member layout. In this way, standardized importance factors that are not used for all buildings. Customized member index computation is conducted based on the geometry, member distribution, and similar factors. Complicated distribution of the importance factors over the plan of structure is demonstrated with the application of the proposed method to different buildings in Chapter 5.

5. Factors that effect importance factor distribution are determined as follows:
   - Location. (Members that are positioned on locations where the irregularity in the plan exists have relatively high importance.)
   - Neighbor members. (Members located in the neighborhood of stiff members are relatively less important than the other members.)

- Capacity check methods. Failure mechanisms are directly related with the member capacity check procedures (e.g., consider shear failure or not). Therefore applied procedures change the importance distribution of members.

6. Sequential collapse analysis is a very important part of importance factor analyses. Some member may not have much of a contribution to the energy dissipation of a building during seismic excitations; however, the same member may have an important function to keep the stability of a local area. The CAVAS program considers simulation of attached member collapses, even if a member is not very strong. The calculated importance factors may also reflect the importance of members from a strategical point of view when the optional sequential collapse tool is activated.

7. The importance of the beams should be included in the vulnerability assessment procedures. As demonstrated in Chapter 5, floor beams have significant contribution to the energy dissipation capacity of a building as a whole, although the importance factor of a single beam is insignificant.

7.3 INTENDED FUTURE STUDIES

Intended future studies are listed below:

- Improvement of sequential collapse analyses with additional implementations and graphical representation support.
- To improve vulnerability index calculation procedure proposed in this study in to vulnerability assessment or performance level estimations by calculating indexes for numerous buildings, which have suffered an earthquake. Matching the index intervals against performance levels (such as light, medium, heavy damage levels or immediate occupancy, life-safety, collapse levels) would allow projection of undamaged building performance and evaluation.
- Try alternative indices by modifying member capacity evaluation procedure.
- Implement more functionality with 3D graphical user interface development.

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APPENDIX A

SEQUENTIAL COLLAPSE

A.1 INTRODUCTION

During earthquakes, the structural behavior of buildings changes based on two main reasons:

1. Change in Member Attributes.
2. Change in Structure Attributes.

The effect of member attributes on the structural response is explained in chapters 1 to 5. Structural attribute refers to the connectivity of the members and diaphragm behavior of the floors. This attribute is not directly related with individual member responses.

In this study with a module called “Failure Simulation Module”, failure of the building is optionally simulated as the analyses continue. With this module, besides member behavior and capacity, the connectivity of members and consequences of member failures are evaluated. Application of this evaluation scheme under earthquake is not in the scope of this study. But the consequences of this procedure are studied with pushover analyses.

During pushover analyses, floors keep diaphragm property through out the analyses. Even if the beams fail which are surrounding the parcel, shells remain stable and continue transmitting load between columns. This behavior guarantees stability of the structure until the instance that overall stability is lost. At this stage the main point that must be questioned is relying on the strength of floors after the beams fail.

In “Failure Simulation Module” the shell distribution is modified during the analyses. The failure criteria of the floors are determined with the failure of beams since floor loads are carried by beams and in the absence of beam, the part of the floor, which is in contact with the removed beam, is not effective. This fact is simulated with the removal of shell that connected to the failed beam. Proposed modification does not remove connectivity provided by floor between columns immediately but changes the load distribution. Briefly as the beams fail, the shell elements connected to beams fail.

When failure simulation module is activated, the stability of the members must be checked at each stage of the analyses. As the member and shell removal take place, the members, which lose stability, are removed from the structure to let the analysis continue. This overall behavior is called Sequential Collapse procedure

The basic concepts implemented to simulate “Sequential Collapse” are described as follows:

- If a beam fails, the connected shell element is removed to simulate crush of the part of floor.
- A shell element, which is connected to the other shells with one joint only, is removed. This fact is shown in Figure A.1. In such a situation shell 1 is removed because with this configuration load transfer is not possible in reality.

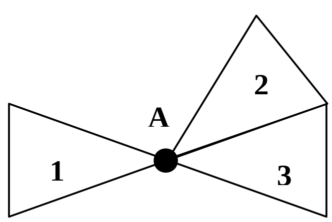

Figure A.1 Shell Stability Control

- If base joints of columns or shear walls are free, than these members are removed. Removal is required in two aspects.
  - A column or shear wall, which has a free base node, indicates that the member does not carry load, any more.
  - During failure simulation, all members that are connected to a column or shear wall may be removed. In this case, member stands without any connection and this yields stability problem.
- Cantilever beams which have plastic hinge at connected joint, are removed.
- At each step all the members that are not connected at both ends are searched and removed.
- Member removal procedures due to shear failures are applied besides this module.

A.2 FAILURE SIMULATION DEMONSTRATION

Sequential Collapse procedure helps the engineer to observe the weak parts of the structure and figure out possible failure mechanisms. For demonstration, procedure is applied to building, which is defined in section 5.3.4 with some modifications. Instead of CT01(see Figure 5.92) and SWT02 (see Figure 5.93), the section displayed in Figure A.2 is used. List of members with assigned section types are displayed in Table A.1. 3D view and plan views of the building are given in Figures A.3 to A.5. As observed in Figure A.5, the member layout of this building is different from Building 4.

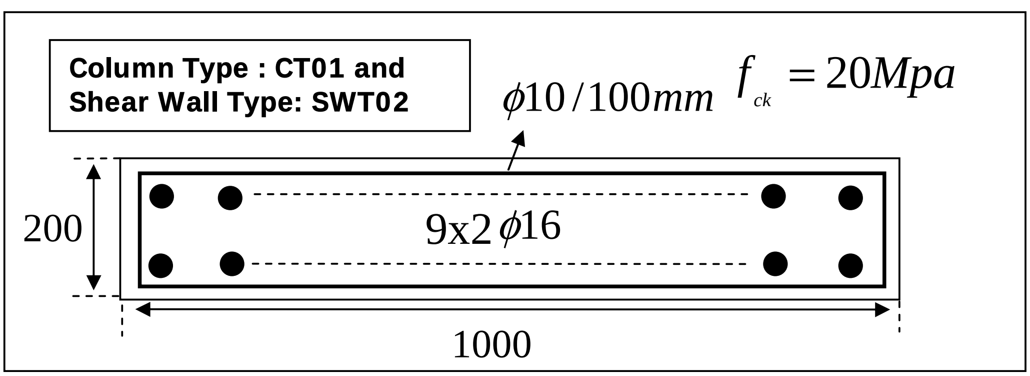

Figure A.2 Details of Column Type CT01 & Shear Wall Type SWT02

Table A.1 List of Members with assigned Section Types

1st Floor Beams	
Member Label	Section Type
B0101	BT01
B0102	BT01
B0103	BT01
B0104	BT01
B0105	BT01
B0106	BT01
B0107	BT01
B0108	BT04
B0109	BT01
B0110	BT06
B0111	BT07
B0112	BT01
B0114	BT02
B0115	BT02
B0116	BT02
B0117	BT01
B0118	BT08
B0119	BT01
B0120	BT01
B0121	BT01
B0122	BT01
B0123	BT01
B0127	BT01
B0128	BT01

1st Floor Columns	
Label Member	Section Type
C0101	CT01
C0102	CT01
C0103	CT01
C0104	CT01
C0105	CT01
C0106	CT01
C0107	CT01
C0108	CT01
C0109	CT01
C0110	CT01

1st Floor Shear Walls	
Member Label	Section Type
SW0101	SWT01
SW0102	SWT02
SW0103	SWT02

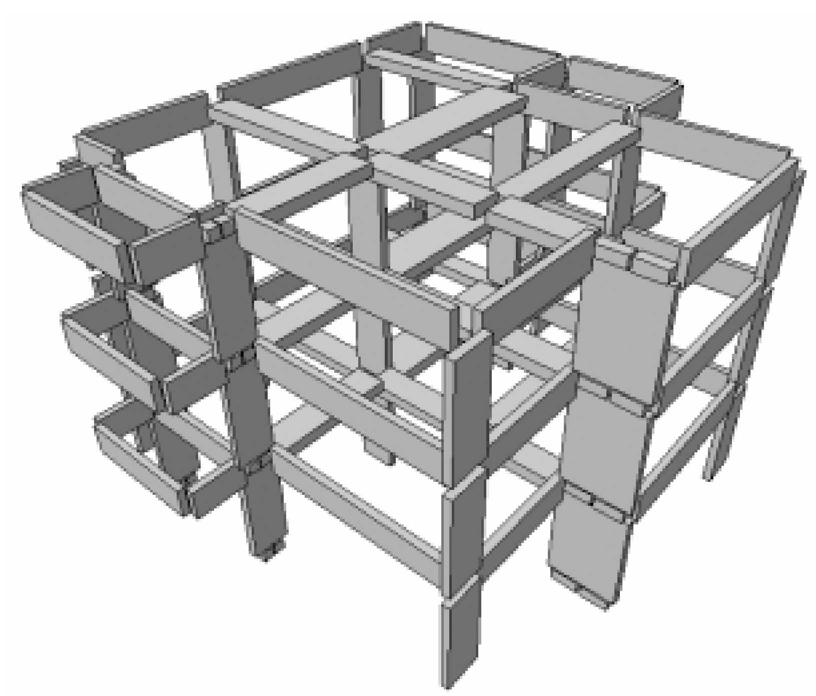

Figure A.3 3D Model of Building

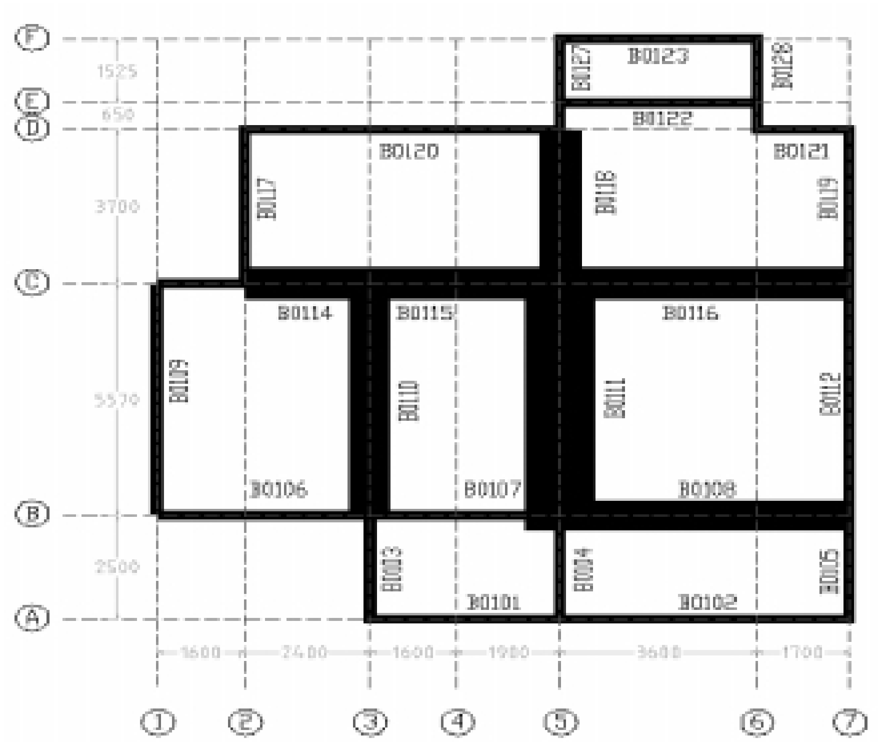

Figure A.4 First Floor Beam Layout of Building

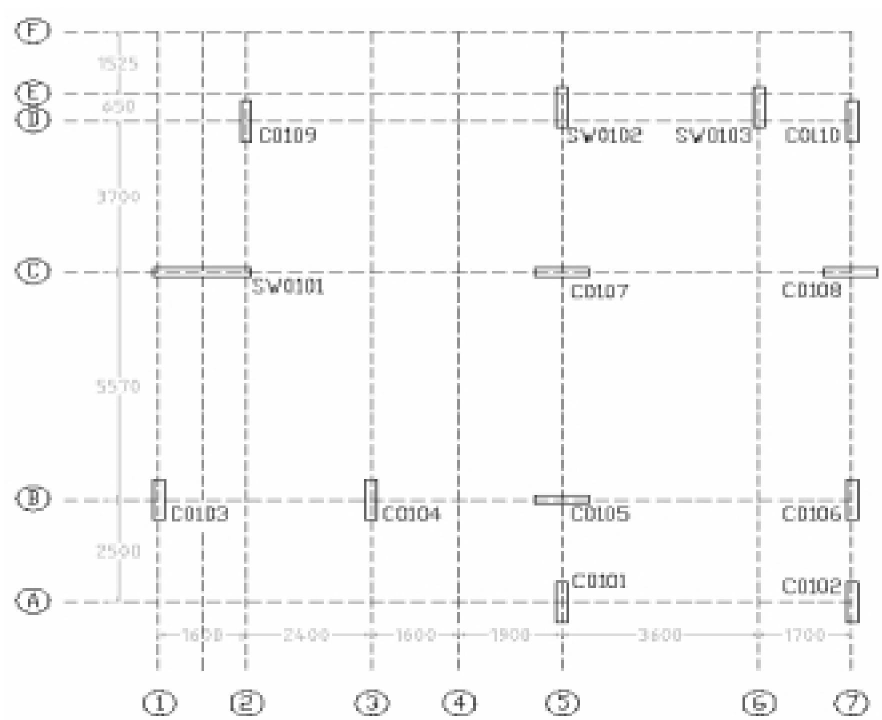

Figure A.5 Base Floor Column & Shear Wall Layout of Building

Besides failure simulation facility, in order to show the flexibility comes with CAVAS, the design check options are revised for this analysis as follows:

- Bresler's formulation is used for P-M-M design check
- Yielding of shear walls with about their strong axis is not allowed.

Failure simulation option is enabled and analysis is conducted. The stepwise failure scheme is presented in Figures A.6 to A.15. The stages without failure are not presented. The failure formation steps are briefly explained below.

- Figure A.6 shows the initial stage of the building without any damage.
- At drift value of 54 mm beams B0118 and B0218 fail due to shear crushing. The shell members that are connected to the beam are also removed. Shear wall SW0101 fails at this stage. This is shown in Figure A.7.
- Until drift of 90mm is reached, no other damage is observed.
- At drift value of 90mm at backside of the building two more beams B0111 and B0112 fail due to shear crushing. Connected shell members are also removed as shown in Figure A.9.
- Figure A.10 shows the failure observed at drift value of 105mm. Beam B0117 fails and connected shell member is removed. At this stage the situation indicated in Figure A.1 is observed. Cavas remove the shell member, which is connected with one joint to other shell elements in the parcel. In this step failure of column C0109 also take place due to shear crushing. This failure changes the force distribution considerable.
- One step after, at drift value of 108mm, one part of the building collapses due to cantilever effect. The failures in previous step, which are demonstrated in Figure A.10, yields failure to progress. The collapsed part is shown in figure A.11.
- As the analyses progress, beams B0110, B0210, B0310 and B0119 fail due to shear crushing as observed in Figures A.12, A.13 and A.14.
- Figure A.15 shows the stage at which mechanism is formed.

Although the relation between member importance factors and failure simulation is not studied in this thesis, the important correlation between them should be emphasized here. The concept of "Local Importance" defines the importance of a member for a part of the building. The failure of a member may yield local failure in the building and this event can not be realized when pushover curves are studied. So to get more realistic member importance factors in a building, study of below mentioned two items is recommended:

1. Contribution of the member to the energy dissipation capacity of the building.
2. Local function of the member.

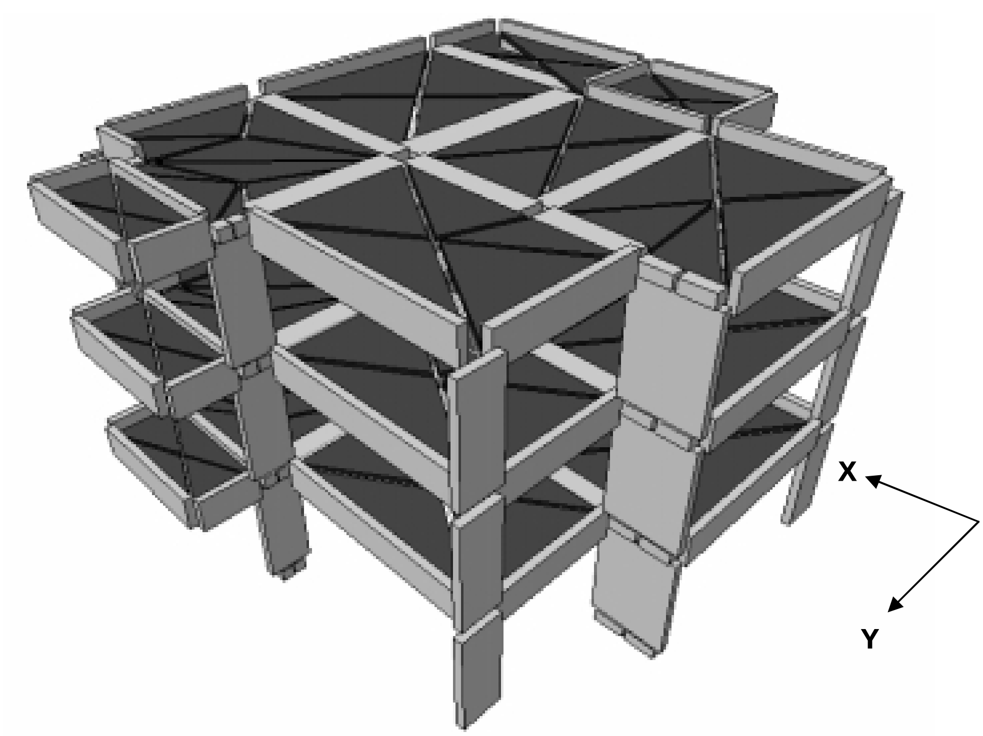

Figure A.6 Initial State of Building

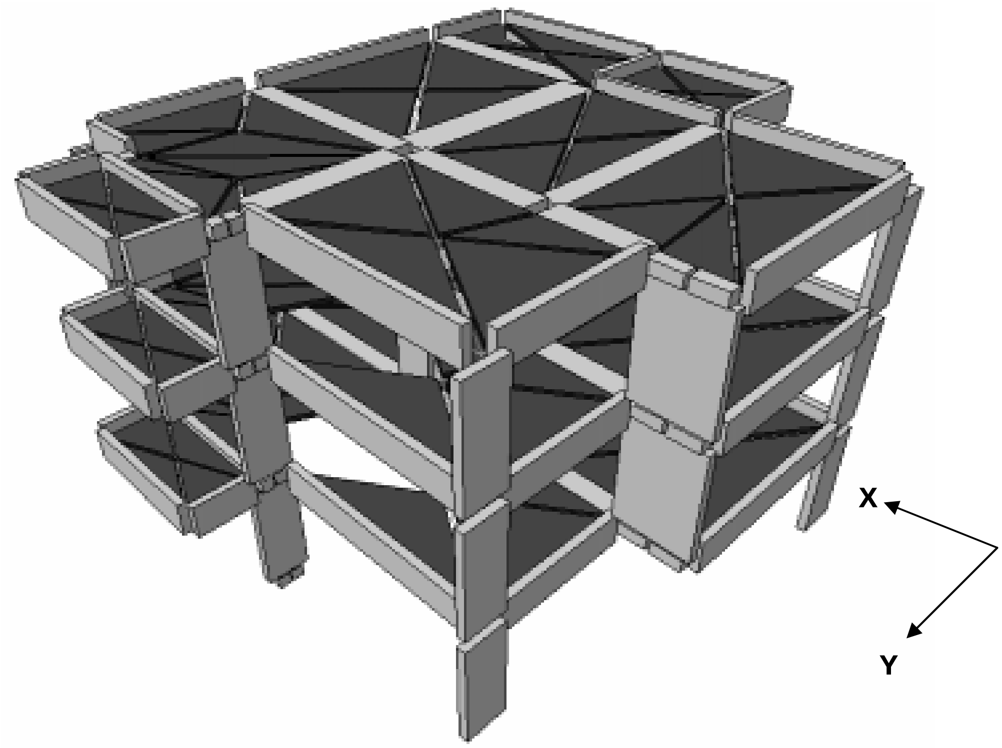

Figure A.7 State of Building at Drift of 54mm

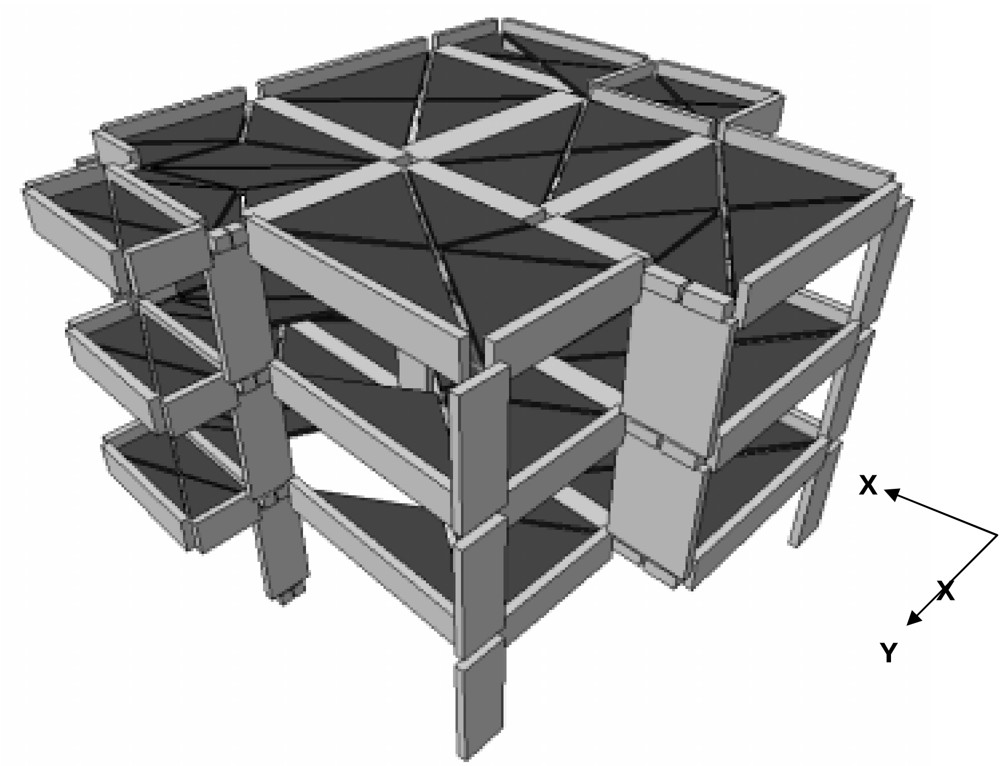

Figure A.8 State of Building at Drift of 90 mm

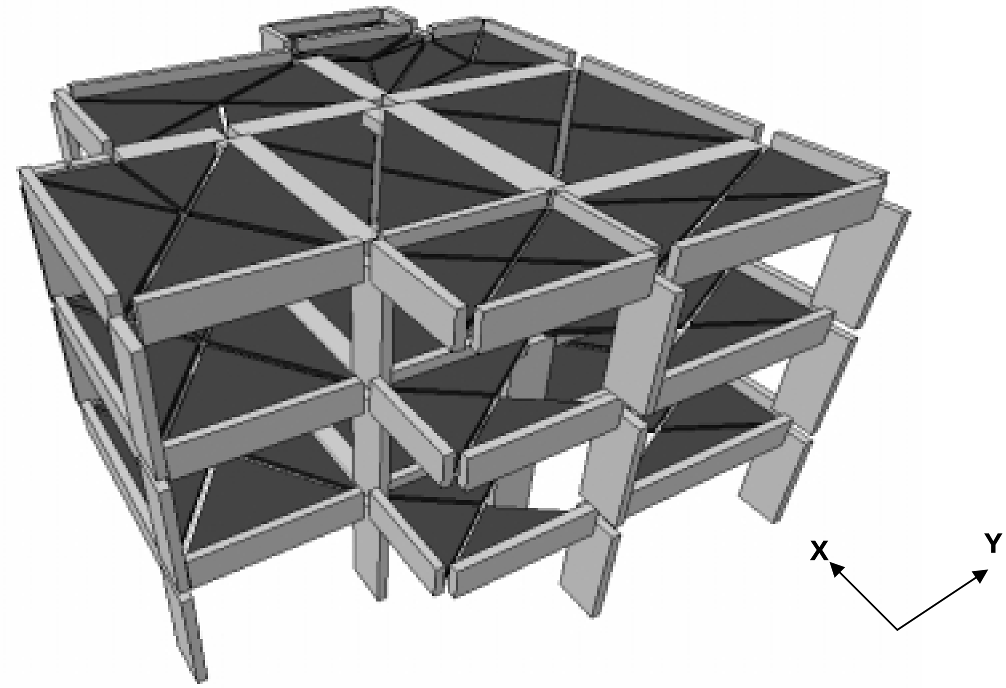

Figure A.9 State of Building (Back Side) at Drift of 90 mm

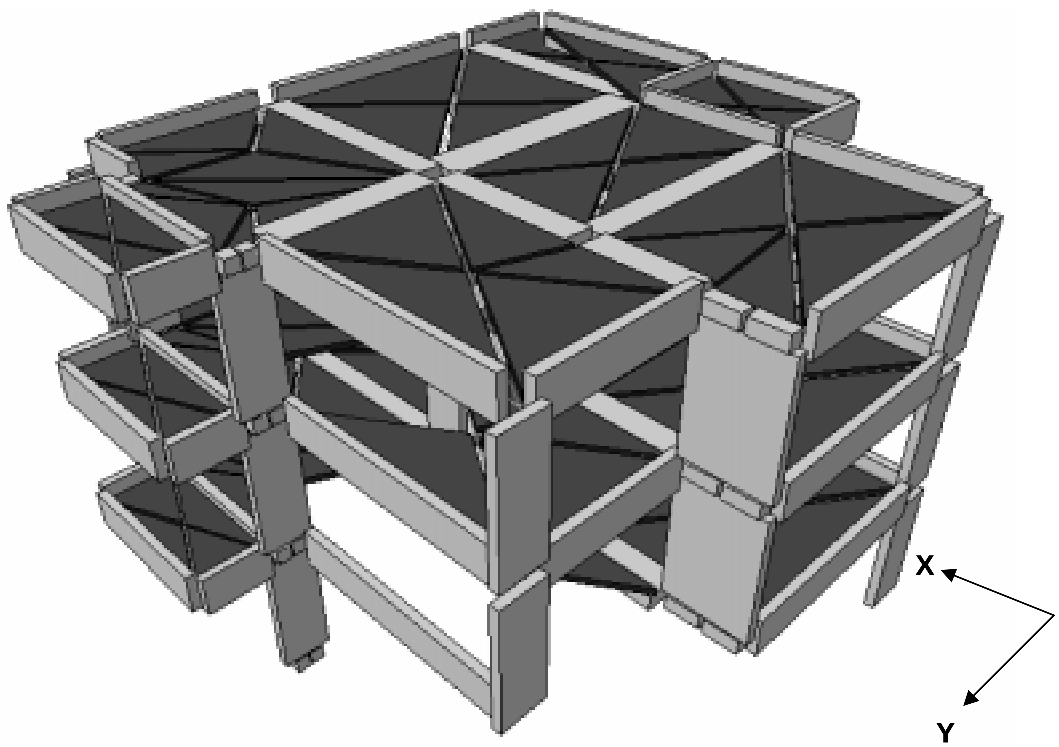

Figure A.10 State of Building at Drift of 105 mm

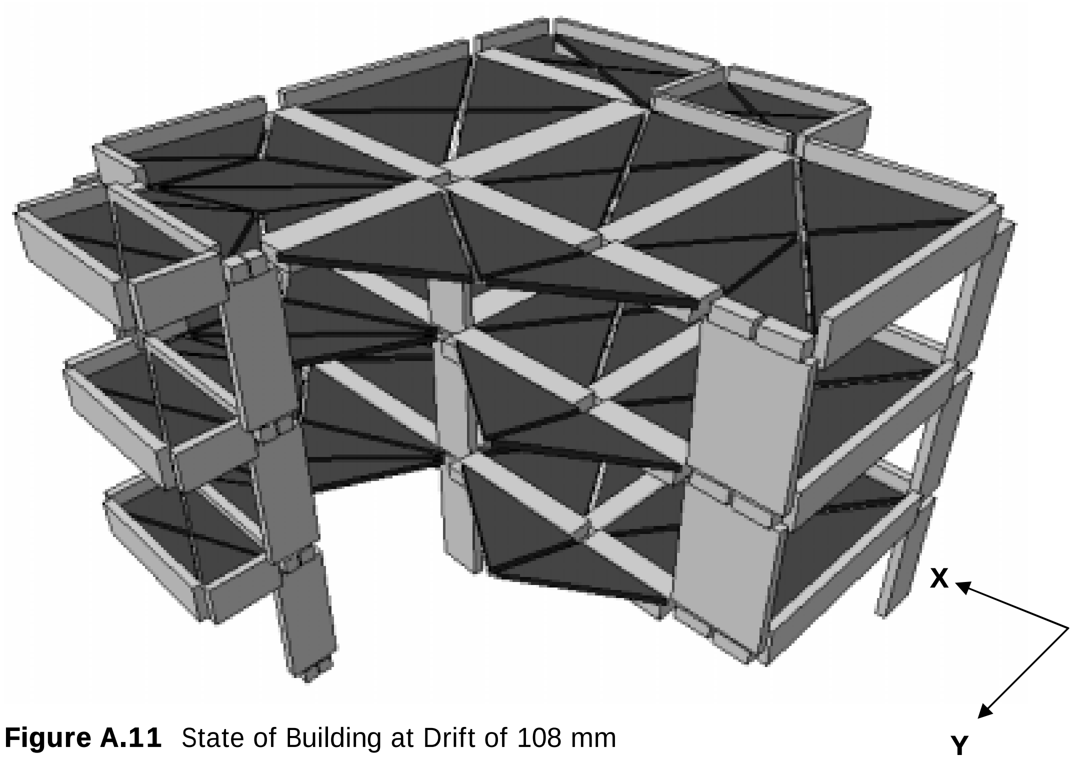

Figure A.11 State of Building at Drift of 108 mm

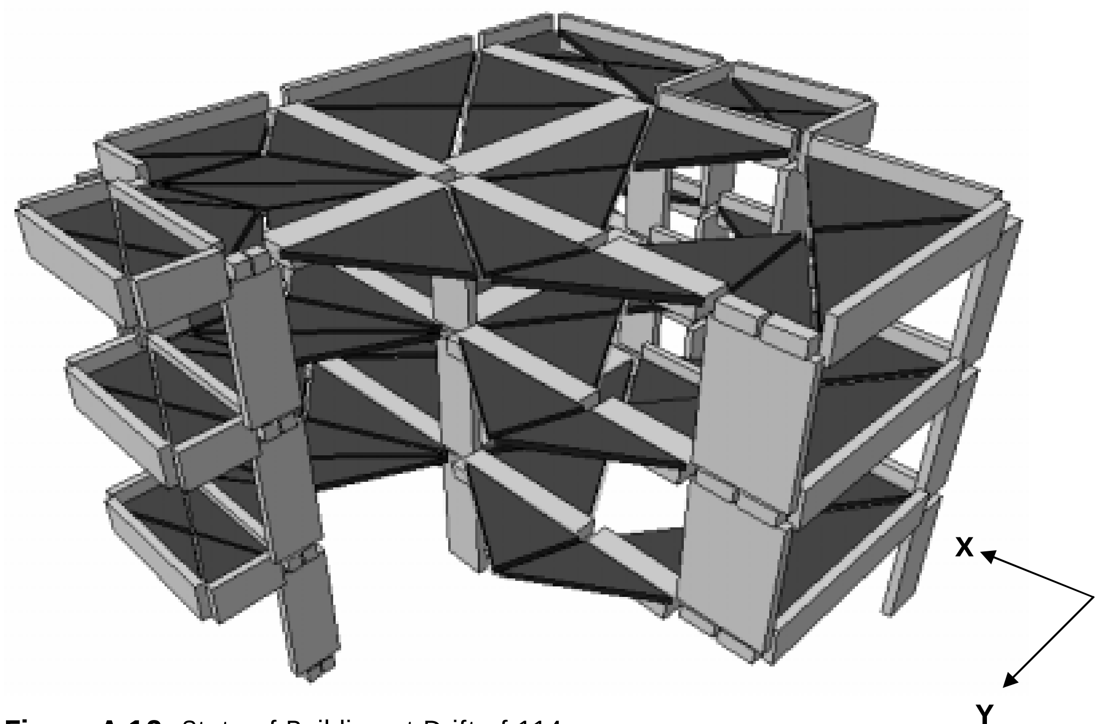

Figure A.12 State of Building at Drift of 114 mm

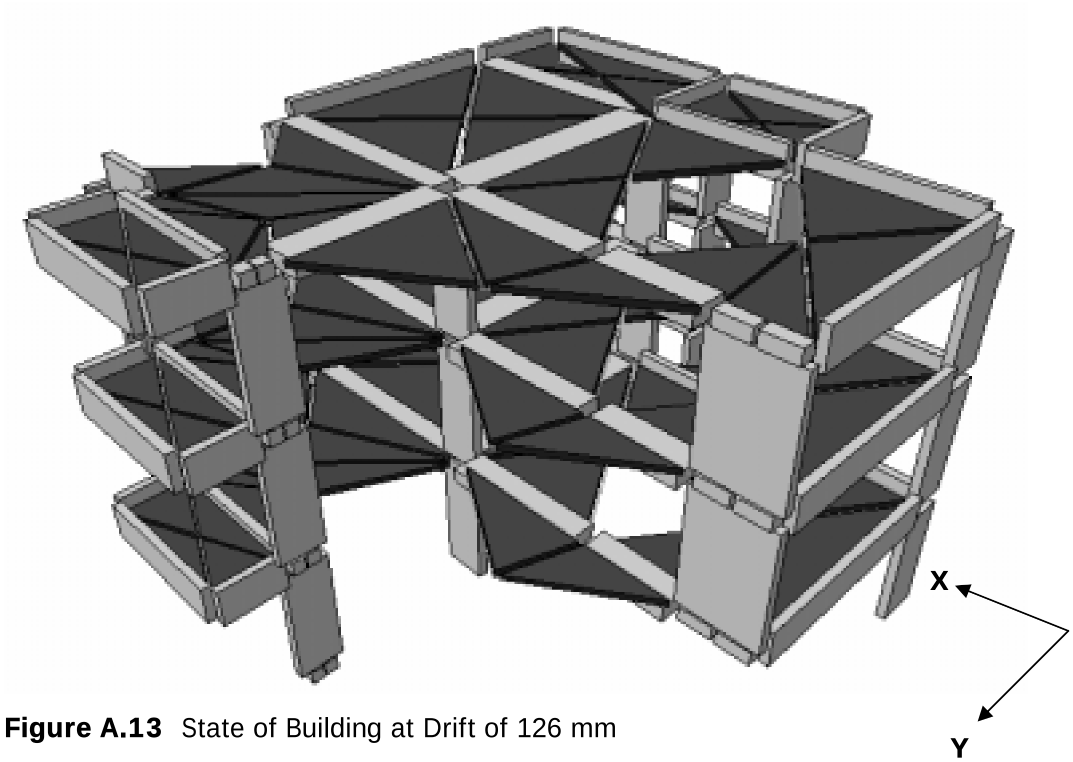

Figure A.13 State of Building at Drift of 126 mm

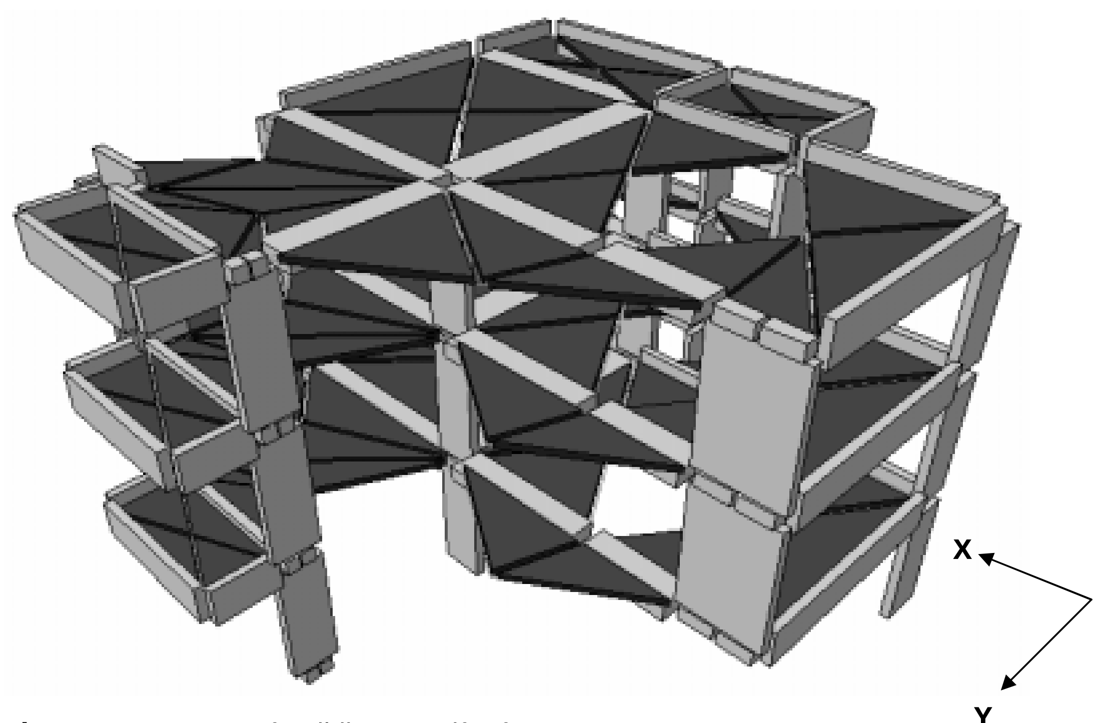

Figure A.14 State of Building at Drift of 138 mm

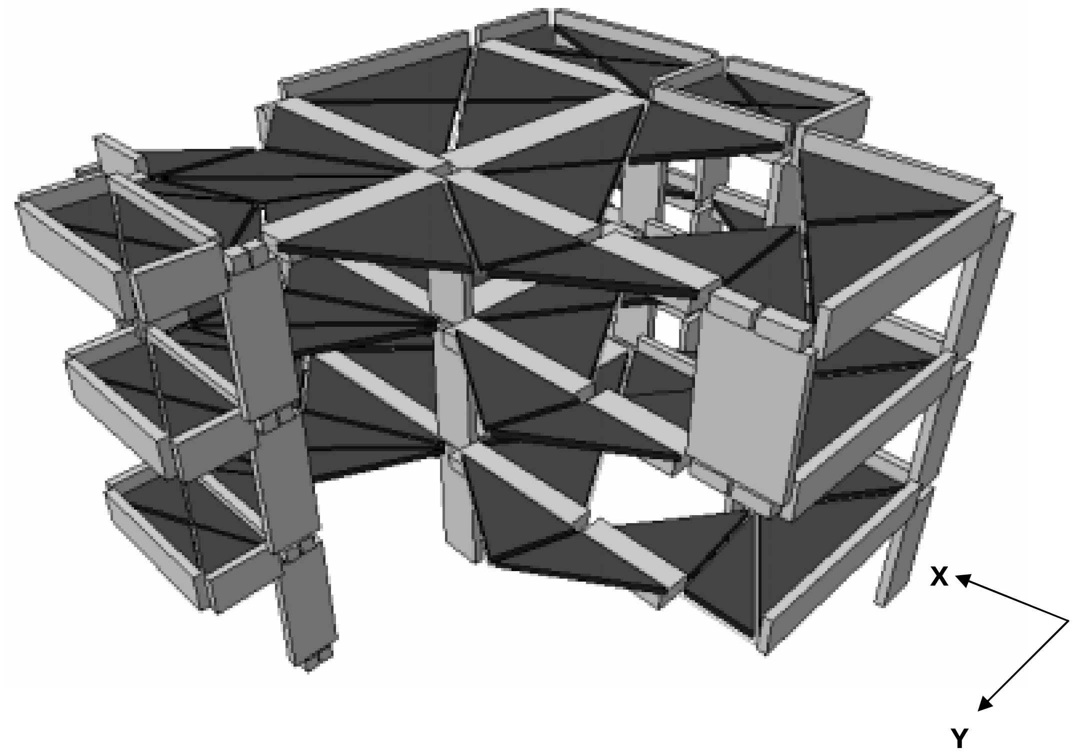

Figure A.15 State of Building When Mechanism is formed at Drift of 141 mm

APPENDIX B

SOFTWARE VERIFICATION

B.1 SOFTWARE VERIFICATION

In this part verification of the CAVAS software is conducted using commercially available analysis software SAP2000 and the results are presented.

The building, which is used for verification analyses, has following properties:

- Building has 2 stories and 2 bays in X direction and 3 bays in Y direction. 3D model of building with floor plan dimensions are displayed in Figure B.1
- Details of the sections used in building are displayed in Figures B.2 to B.3. All of the columns are same with section type displayed in Figure B.2. All of the beams are same with section type displayed in Figure B.3.
- All floor heights: 2.95 m.
- Building is symmetric in plan and has no elevation irregularities.

Same verification procedure, which is explained in section 5.2.1, is applied for the test building.

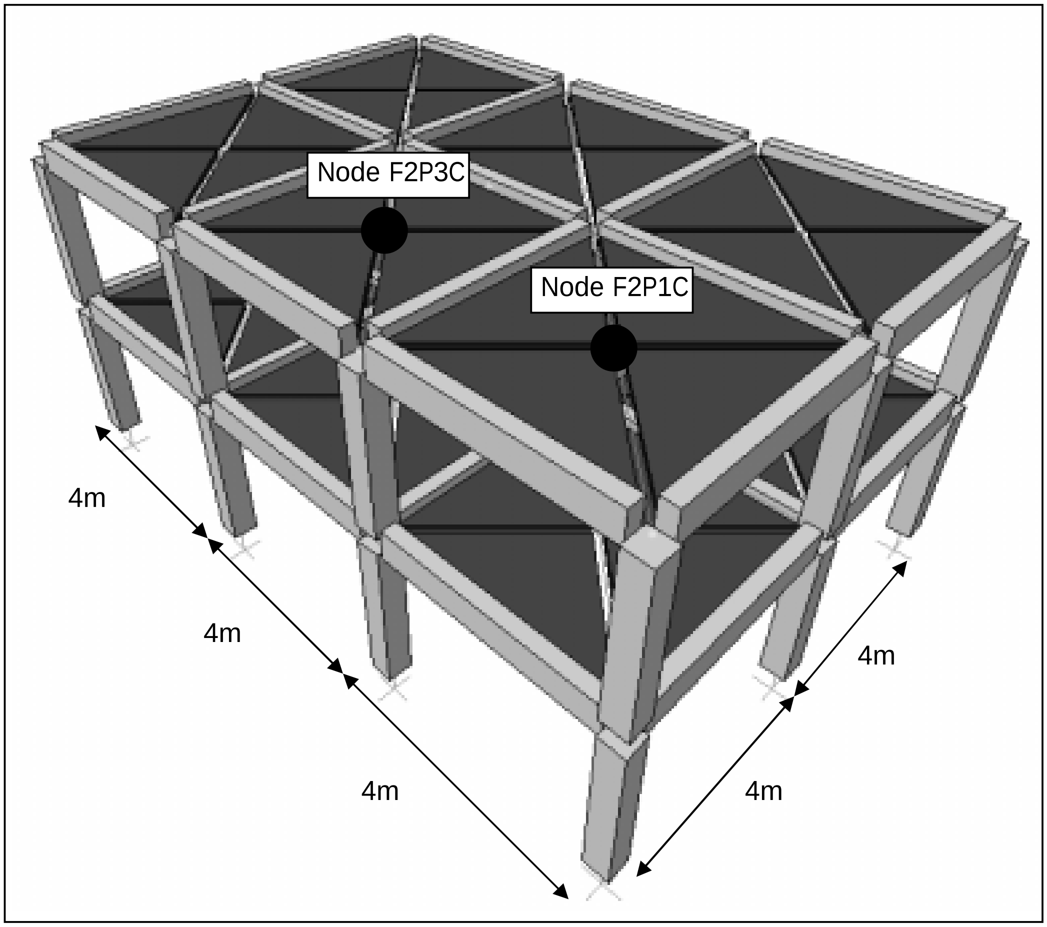

Figure B.1 3D Model of the Test Building with Floor Plan dimensions

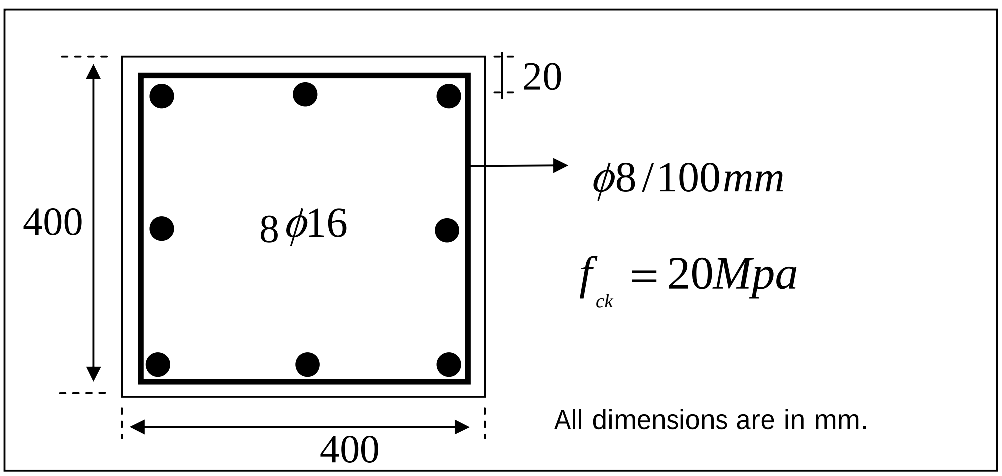

Figure B.2 Details of Columns

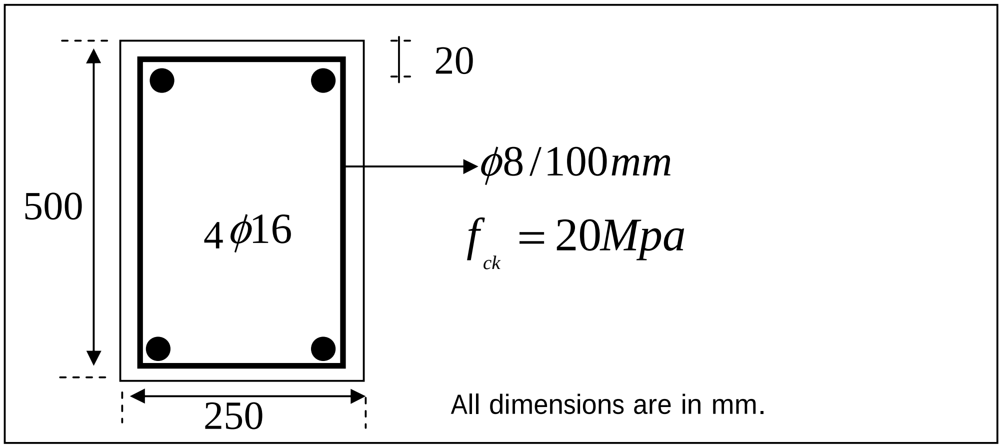

Figure B.3 Details of Beams

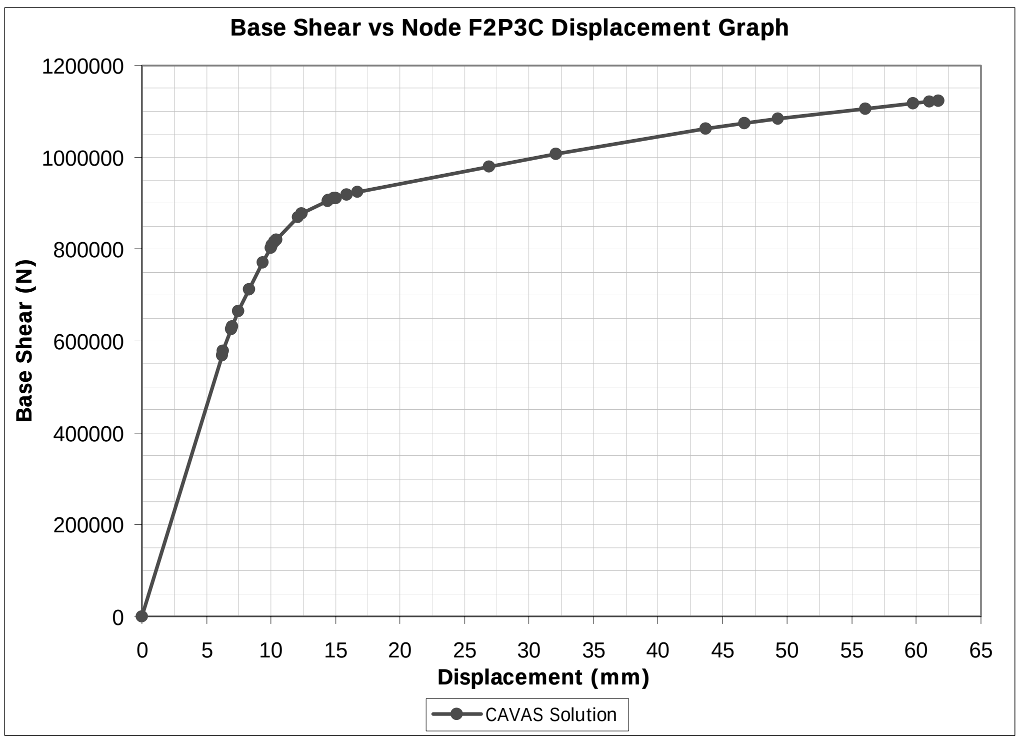

Figure B.4 CAVAS Pushover analysis result conducted in X Direction

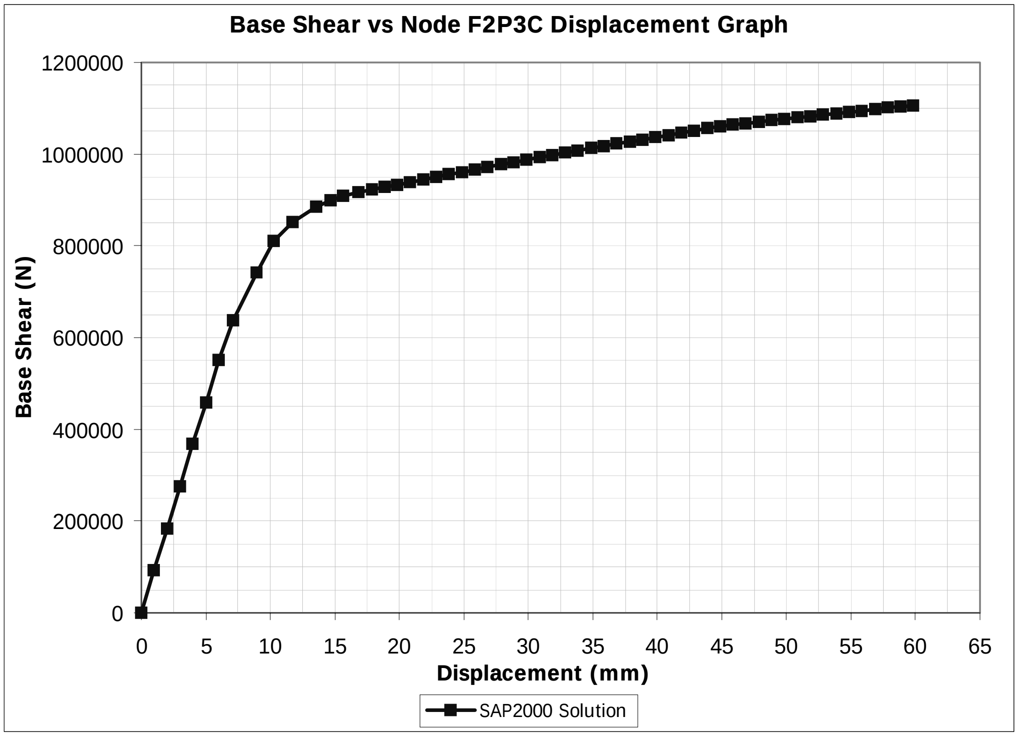

Figure B.5 SAP2000 Pushover analysis result conducted in X Direction

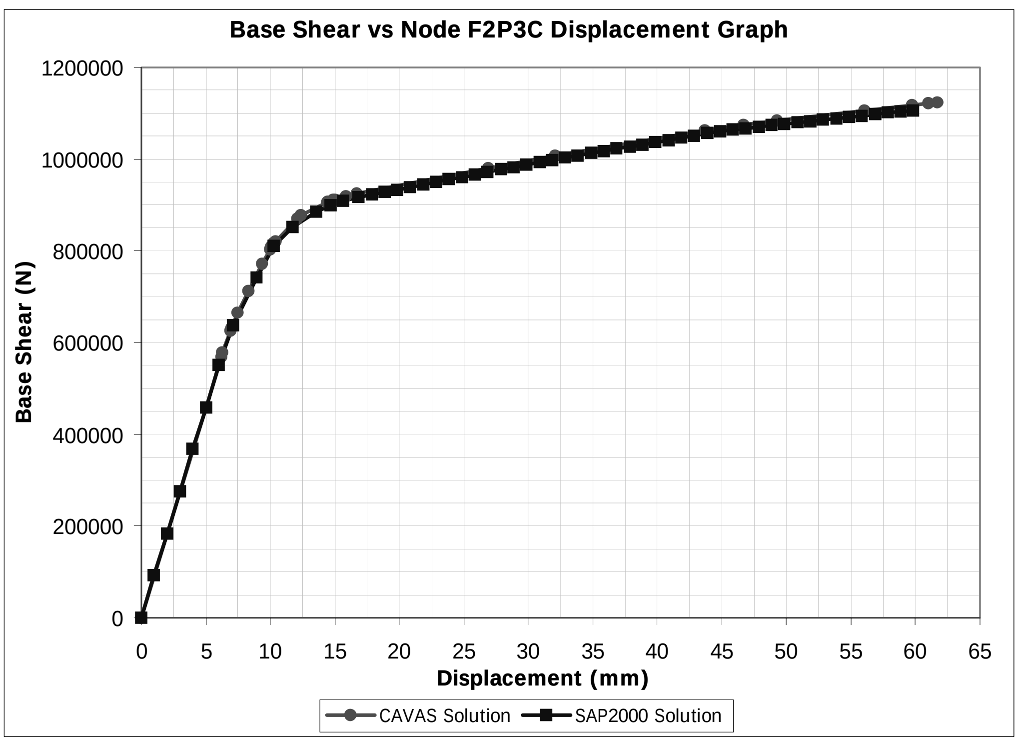

Figure B.6 Pushover Curves obtained by CAVAS and SAP2000 in X Direction

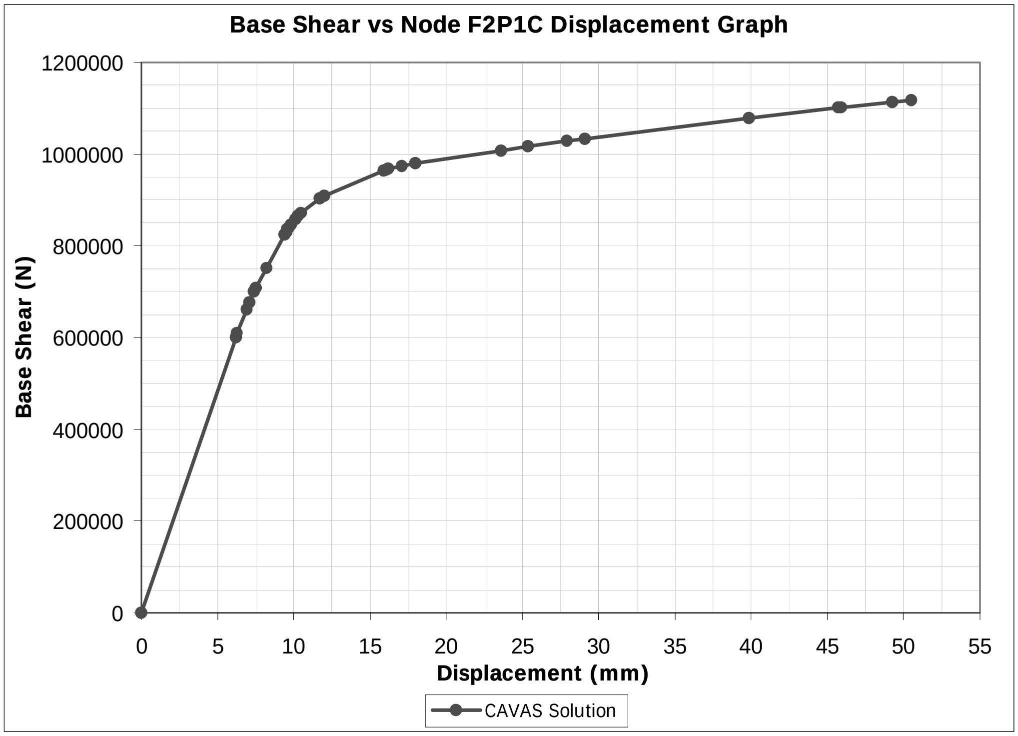

Figure B.7 CAVAS Pushover analysis result conducted in Y Direction

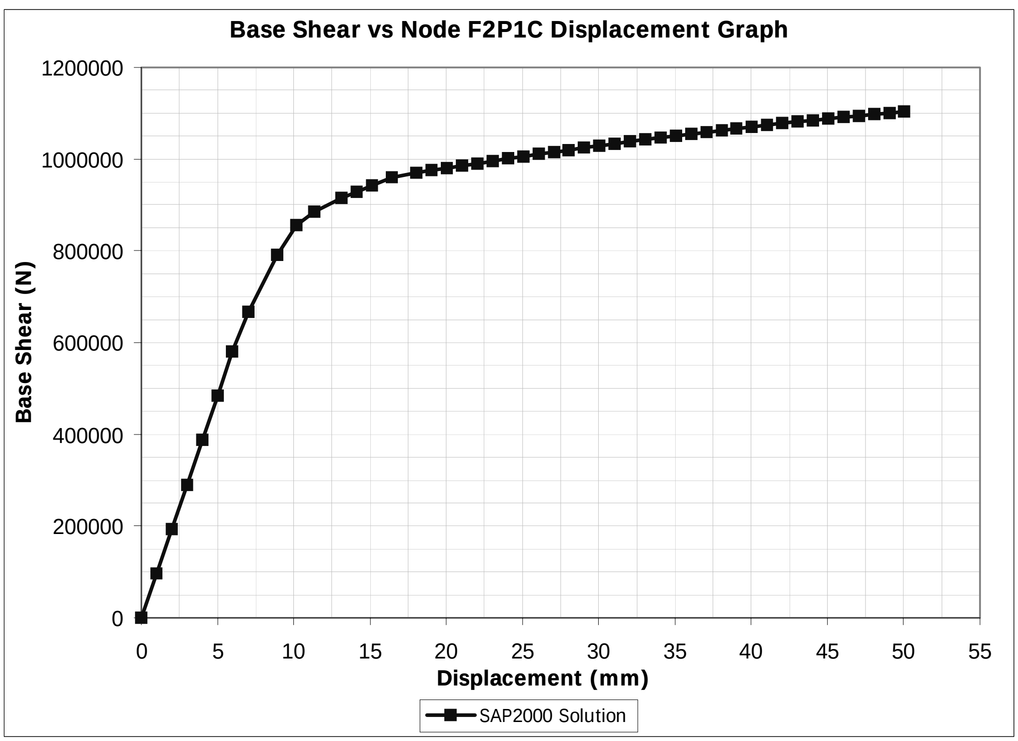

Figure B.8 SAP2000 Pushover analysis result conducted in Y Direction

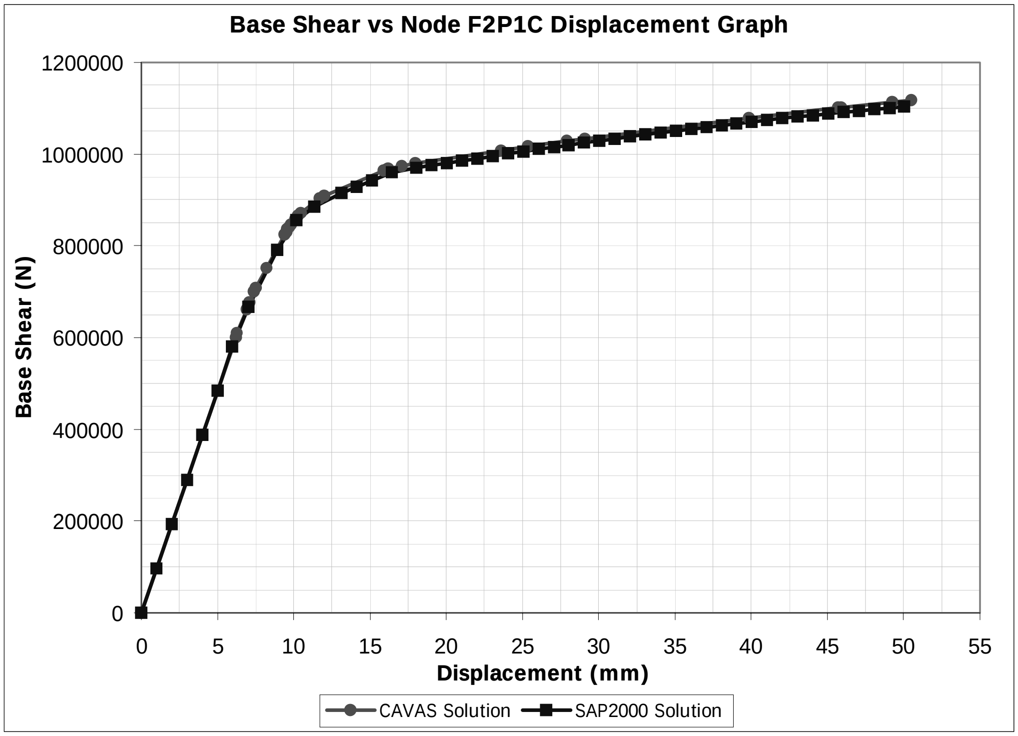

Figure B.9 Pushover Curves obtained by CAVAS and SAP2000 in Y Direction

B.2 Discussion of Pushover Analyses Results

The results of analyses that are conducted by CAVAS and SAP2000 with X dominant mode shape are displayed in Figures B.4 and B.5, respectively. The comparison graph for X dominant direction pushover analyses is displayed in Figure B.6. The results of analyses that are conducted by CAVAS and SAP2000 with Y dominant mode shape are displayed in Figures B.7 and B.8, respectively. The comparison graph for Y dominant direction pushover analyses is displayed in Figure B.9.

The consistency of the pushover curves indicates that for symmetric buildings pushover module implemented in CAVAS gives reasonable results.