Linear and Non-Linear Static Progressive Collapse Analysis of Steel Framed Buildings with I-Beams and Truss Beams

Buğse İlman

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirement for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
September 2017
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Assoc. Prof. Dr. Ali Hakan Ulusoy
Acting Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Assoc.Prof. Dr. Serhan Şensoy
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Mürüde Çelikağ
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Mürüde Çelikağ ______________________________
2. Asst.Prof. Dr. Abdullah Fettahoğlu ______________________________
3. Asst. Prof. Dr. Umut Yıldırım ______________________________

ABSTRACT

Progressive collapse is the collapse of a considerably large part of a structure as a result of failure of its relatively small part. After the progressive collapse (PC) of the Ronan Point apartment tower in England in 1968, prevention of progressive collapse became one of the challenges of structural engineers. Since then, researchers carried out many studies on progressive collapse. In addition, General Services Administration (GSA), Department of Defense (DoD), and Unified Facilities Criteria (UFC) developed guidelines for assessing and preventing progressive collapse. Furthermore, NIST (National Institute of Standards and Technology) has published a list of potential load hazards that might generate progressive collapse. This study used GSA guidelines to investigate the progressive collapse potential of an eight story steel framed building by using I-beams and trusses as floor beams. Linear and nonlinear static analysis were used to assess the potential of PC by using the general purpose computional analysis program ETABS. Structural members PC potential is assessed according to Demand Capacity Ratio (DCR) for linear static analysis and rotation for nonlinear static analysis. The results show that, after removing the columns for linear static analysis, floors with truss beams had DCR values less than the floor with I-beams. The results of nonlinear static analysis indicate that the floors with I-beams had greater rotation values than the floors with truss beams. As part of Alternative Path Method, new bracings introduced in the bay adjacent to the removed column to rehabilitate the buildings.

Keywords: Progressive collapse, linear static analysis, nonlinear static analysis, truss beams, I-beams.

ÖZ

Aşamalı çöküşün başlamasına neden genelde lokal hasarlardır. Bunun yanı sıra birkaç elemanın kırılışı sonucu yapının daha büyük bir kısmının çökmesi de aşamalı çöküşün başlamasının nedenlerinden biridir. Yakın zamanlarda meydana gelen ABD'de Ticaret Merkezi binasının aşamalı çöküşü gibi felaketlerin olasılığını azaltmak ve önlemek için yapı analizi ve tasarımı yapılırken bir dizi önlemlerin alınması artık ihtiyaç olmuştur. Buna ek olarak, yapıların aşamalı çöküşe karşı dayanımını artırma yöntemleri araştırılabilir. Bu araştırmada I-kirişi ve kafes kiriş döşeme sistemi olan çelik karkas yapılarda aşamalı çöküş potansiyeli araştırılmıştır. Bu nedenle bahsekonu çelik karkas yapıda doğrusal statik ve doğrusal olmayan statik analiz metodları ile aşamalı çökme potansiyeli etkisi araştırılmıştır. Genel Hizmet İdaresi (GSA) ilkeleri, doğrusal statik analiz metodu ve doğrusal olmayan statik analiz metodu kullanılarak yapı analiz edilmiştir. Doğrusal statik analiz metodu sonuçlarına göre I-kirişli döşemeli yapıların tüm kiriş açıklıklarında aşamalı çöküş potansiyeli kafes kiriş döşemeli yapılara göre daha fazladır. Buna ek olarak, doğrusal olmayan statik analiz sonuçlarına göre kafes kiriş döşemeli yapıların tüm kiriş açıklıklarında aşamalı çöküş potansiyeli I-kirişli döşemeli yapılara göre daha azdır. Tüm yapısal elemanların, doğrusal statik analizinden DCR değerleri ve doğrusal olmayan statik analizinden rotasyon değerleri bulunmuştur. Daha sonra kabul değerlerini geçen tüm elemanlar için kolon eksiltilen bölgeye komşu bölgede yeni destek sistemi kullanılarak yapısal elemanlar rehabilite edilmiştir.

Anahtar Kelimeler: Aşamalı çöküş, doğrusal statik analiz, doğrusal olmayan statik analiz, kafes kiriş ve I-kiriş.

Tezimi, beni koşulsuz sevgi, sabır ve emeği ile büyütüp, bugünlere gelmemi sağlayan değerli anneme ithaf ediyorum.

ACKNOWLEDGMENT

I would like to exprees my gratitude to my supervisor, Assoc. Prof. Dr. Mürüde Çelikağ whose expertise, proficiency and patience added to my knowledge. I appreciate all her efforts. In addition, without her invaluable supervision, I would not have finished this thesis.

I would like to declare my appreciation to my mother for supporting and encouraging me in this specific case. Her motivation and encouragement is so valuable for words to express.

I have to emphasize the great support I have received from my friends Ali Sadeghpour and Ahmad Alkhouzei in Civil Engineers Department. I fully appreciate their help which truly contributed to this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PC	Progressive Collapse
RB	Regular Building
IR8F	8 Floors Irregular Building
IR4F	4 Floors Irregular Building
RB-I	Regular Building with I-Beams
RB-T	Regular Building with Truss Beams
IR8F-I	8 Floors Irregular Building with I-Beams
IR8F-T	8 Floors Irregular Building with Truss Beams
IR4F-I	4 Floors Irregular Building with I-Beams
IR4F-T	4 Floors Irregular Building with Truss Beams
GSA	General Services Administration
UFC	Unified Facilities Criteria
DoD	Department of Defense
NIST	National Institute of Standards and Technology
ASCE	The American Society of Civil Engineering
DCR	Demand Capacity Ratio

Chapter 1

INTRODUCTION

1.1 General Introduction

Civil engineering is a broad field of engineering dealing with the planning, construction and maintenance of structures . Through their design they should conform to the acceptable criteria. Design of structures should be safe while supporting loads by taking into account changing climate and natural disasters, such as, earthquakes, hurricanes, tornadoes, floods, fires, explosion and impact. Collapse of structures might have several causes, such as, The 1994 Northridge earthquake, bombing of Murrah Federal Office Building in 1995, and the terrorist attack on the World Trade Center I and II in 2001.

The progressive collapse (PC) has a variety of descriptions. General Services Administration (GSA,2003b) describes it as: ‘‘Progressive collapse is a situation where local failure of a primary structural componenet leads to the collapse of adjoining members which, in turn, leads to additional collapse’’. Song et al. (2010), defined PC as an accidental event caused by a man made or natural disaster. For example, the Murrah Federal Office Building in Oklahoma City was destroyed by a bomb in 1995, caused loss of lives and finance because of PC. There are several methods developed with the aim of minimizing the possibility of progressive collapse in existing structures.

The following are the most widely used guidelines for assessing possibility of PC and then taking measures to prevent it. GSA (GSA, 2003), Unified Facilities Criteria (UFC, 2003), NIST (National Institute of Standards and Technology) (NIST, 2005) and

Department of Defense (DoD) (DoD, 2005). GSA, DoD, UFC and NIST refers to indirect and direct methods to evaluate potential of PC.

- Indirect design method: requires consideration of minimum strength, connections for resisting progressive collapse.
- Direct design method: interested in the structures resistance to PC (ASCE, 2005).

The Alternate Load Path (ALP) method is used by the guidelines to simulate the PC risk of a structure (Kaewkulchai & Williamson, 2003).

Designs based on the ALP analysis lead to larger member sizes than those obtained from normal design approach where all applicable load combinations are used. Consequently, a way of retroffiting existing structures is needed for reducing the potential of PC, (Ruth et al., 2006).

1.2 Significance of Progressive Collapse

PC is a relatively rare event in developed countries since it requires both an abnormal loading to initiate the local damage and a structure must have inadequate continuity, ductility, and redundancy to resist the spreading of damage. However, significant casualties can result when collapse occurs. Consideration of preventative measures for PC on buildings is an expensive activity. It requires serious consideration of continuity and redundancy within the structural system. However, in recent years, there is an increased demand on the assessment of buildings towards reducing the PC.

According to NIST, accidental events, errors in design and\or construction process, fire, accidents, blasts and vehicular collusion may lead a building to go through progressive collapses.

1.3 Research Objectives

The aim of this study is to investigate the progressive collapse potential of an eight story building when trusses are used as floor beams. Hence the building is first designed by using I beams. Short side of the structure is a braced frame while the long side is a moment frame. PC potential due to column removal was evaluated by using GSA guidelines together with linear and nonlinear static analysis. Then the primary beams of the braced frame were replaced by truss beams and the same process was applied on this building too.

1.4 Tasks

The specific tasks of this study are shown below:

1. An eight story dormitory building was modeled by using ETABS software program [ETABS version 13.2.2]. The building was first designed by using I-beams as floor beams. Then the building was redesigned when trusses were used as floor beams instead of the primary I-beams. From here on these two building models, one with I-beam floors and the other one having truss beams instead of primary I-beams, are referred to as ‘ Regular Buildings’.
2. Then, some floors were removed from the two regular buildings and hence they become irregular buildings. Floor between gridlines 1-2/C-D, the beam on grid 1/C-D and the secondary beam between grids 1-2/C-D were removed from the eight floors of regular buidings with I-beam and truss beam models. From here on these models are referred to as ‘Irregular Buildings, IR8F-I and IR8F-T. Afterwards, the same irregularity procedure was implemented for the first four floors for regular buildings to obtain the ‘Irregular Buildings, IR4F-I and IR4F-T’.
3. This followed by checking of PC potential when a column is removed from the building. Linear and nonlinear static analysis were used with GSA guidelines.

4. All building types were analyzed and the results of building floors with I-beam and truss beam were compared.
5. After removing a column, the response of building was evaluated. In addition, linear and nonlinear static analyses procedures were implementing according to GSA.
6. Then the Demand Capacity Ratio (DCR) magnitudes of each column and beam for buildings were compared with I-beam and truss beam for linear static models.
7. Finally, for nonlinear static models, the rotation magnitudes of each column and beam for buildings with I-beam and truss beam were compared.

1.5 Outline of the Thesis

The thesis has six chapters, each of which is summarized below:

Chapter 1 is the general introduction to the topic.

Chapter 2 contains Research background on the PC of the buildings. Examples to PC of structures is described. The PC resistance guidelines, GSA and UFC, are described. Similar design methods are also explained in this chapter.

Chapter 3 includes description of the building models used for this study. In addition, 2-D and 3-D ETABS software models for each building type are given.Moreover, buildings structural members, loading conditions and acceptance criteria are explained in Chapter 3.

Chapter 4 provides the results of the 3-D linear static analysis procedure for regular and irregular buildings. Demand Capacity Ratio (DCR) values are also presented for all building types in Chapter 4.

Chapter 5 provides the results of 3-D nonlinear static analysis procedure for regular and irregular buildings. Rotation values are also presented for all building types in Chapter 5.

Chapter 6 provides results, discussion, conclusions and the recommendations for futute study.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Relevant past research details concerning the PC of buildings are given in this chapter. Firstly, the definitions and examples of PC are explained. Also analysis and design guidelines GSA and DoD used for measuring the PC potential of buildings, are introduced.

2.2 Definitions of Progressive Collapse

Man-made hazards such as, blasting, explosion, vehicle collusion or by natural disasters like earthquakes and hurricanes may cause PC. The American Society of Civil Engineering (ASCE) Standard 7-05 defines the PC as "the extend of a preliminary local failure from element to element resulting eventually in the collapse of an entire structure or a disproportionately large part of it" (ASCE 7-05, 2005). While the main objective of progressive collapse criteria is to protect lives, the other objective of progressive collapse criteria is to prevent significant damage to the new or existing buildings.

2.3 Examples of Progressive Collapse

2.3.1 Collapse of Ronan Point Apartment Tower

The 22-story building was located in Newham, England. The collapse was started by a gas leak in a corner kitchen. Figure 2.1 shows the part of collapsed building. After the PC of the Ronan Point apartment tower in England, prevention of PC became one of the challenges of structural engineering. As a result, there were changes in British and Canadian building codes to accommodate design approaches to resist PC (Griffiths et al., 1968).


Figure 2.1: Ronan Point Apartment in 1968 (Wikipedia, 2012).

2.3.2 Murrah Federal Office Building

The attacking of the Alfred P. Murrah Federal structure on April 19, 1995 in Oklahoma City, USA is one of the well know cases of PC (FEMA-277, 1996). When three columns supporting the transfer beam failed, the columns supported by the transfer beam also failed. Hence, subsequent collapse of the floor areas supported by the columns. As a result of the effect of this huge explosion followed by the collapse, 168 people were killed and over 800 people were wounded (Irving, 1995). The Murrah Building tragedy was obviously a progressive collapse by all the definitions of this term. Figure 2.2 reveals the damage caused by the PC of the building (Nair,2004).


Figure 2.2: Alfred P. Murrah Federal building (FEMA-427, 2003).

2.3.3 Collapse of World Trade Center I-II

As a result of terrorist attacks on September, 11 2001, the World Trade Center twin towers collapsed progressively (NIST, 2005, Dusenberry et al., 2004). Two aeroplanes hit the twin towers one after another at high speed causing fires and progressive collapse of the twin towers, the death of more than 3000 people and extensive range of damage to the neighboring structures (Figure 2.3).

Figure 2.3: World Trade Center twin towers after the terrorist attack (FEMA-403, 2002).

2.4 Design Methods for Progressive Collapse

Indirect and Direct Design Methods presented here help reduce the possibility of PC potential (ASCE 7-05, 2005). Each of these methods are explained in the following sections.

2.4.1 Indirect Design Method (ID)

ID is employed by most widely used standards to prevent progressive collapse (ASCE 7-05, 2005). Generally, 13 building codes and standards use the indirect design approach since it can make a redundant structure that will complete under any situation and improve overall structural response (ACI 318-08, 2008).

2.4.2 Direct Design Method (DD)

During the design procedure the direct design method clearly considers resistance of a structure to progressive collapse (ASCE, 2005). This method is interested in PC resistance of buildings through Specific Local Resistance (SLR) and ALP method (ASCE, 2005). The SLR method trying to improve and provide strength to be capable of resisting progressive collapse. On the other hand the ALP method seeks to give ALP to redistribute load to stronger nearby structural members to constrain damage (ASCE, 2005).

2.4.2.1 The Specific Local Resistance Method

The SLR method attemps to design members to resist a specific abnormal load. The structural member is designed to have extra stiffness and strength to prevent PC by increasing the design load variables (ASCE, 2005).

2.4.2.2 The Alternative Load Path Method

Some design methods have been proposed to prevent progressive collapse of building structures. ALP method is one of the most popular methods where local failure of a primary structural member is allowed . The alternate load path method: Local failure of a primary structural member is allowed for this method. It is not dependent on the beginning of overload and this is one of its advantages (ASCE, 2005).

2.5 Progressive Collapse Analysis Procedures

There are four different analysis procedures for progressive collapse to analyze the structural performance of a building; Linear Static (LS), Nonlinear Static (NLS), Linear Dynamic (LD), and Nonlinear Dynamic (NLD).

2.5.1 Linear Static Procedure

The linear static analysis procedure is performed using an amplified combination of service loads, such as dead and live, applied statically. This analysis procedure is the simplest and easiest to perform. It is hard to forecast exact behavior in a building, owing to the lack of the dynamic result by rapid failure of more members (Kaewkulchai & Williamson, 2003). The linear static analysis procedure may be used when both nonlinear response and dynamic effects can be easily and intuitively predicted.

2.5.2 Nonlinear Static Procedure

Nonlinear static analysis is a good choice for designing of the new buildings. Nevertheless, analyzing and assessing the existing buildings it would take considerably more time to carry out analysis and design. Nonlinear static analyses require reasonably detailed finite element models to represent nonlinear bahavior of the structure, and are time consuming because of the need of step-by-step increase of vertical loads until the structure collapses. In nonlinear static analysis, geometric nonlinearlity resulting from large deformations can be accounted for through the redistribution of loads as a consequence of the elimination of a critical column.

2.5.3 Linear Dynamic Procedure

The Linear Dynamic (LD) analysis procedures are usually avoided, as they are perceived to be excessively complex. But compared to static analysis procedures, their accuracy is much higher since dynamic procedures inherently incorporate dynamic effects, such as, inertia and damping forces. The LD analysis procedure may be used when the nonlinear response of the structure can easily and intuitively be predicted.

2.5.4 Nonlinear Dynamic Procedure

The Nonlinear Dynamic (NLD) analysis procedure is often avoided due to it's complexity in computation. NLD could be time-consuming during the process of getting results but the outcome is more realistic in comparison to other analyis procedures (Marjanishvili, 2004).

2.6 Progressive Colapse Design Guidelines

Designers and architects refer to GSA and UFC documents when designing new buildings and facilities in order to improve the quality of buildings and structures. They are encouraged to ensure that problems related to progressive collapse should be considered to take preventive solutions (Herrle, and McKay, 2005).

2.6.1 Guidelines of DOD

The U.S. DoD supplies a file , “*Design of buildings to resist progressive collapse*”, (DOD, 2005). This guideline details how to evaluate and design the building to prevent PC. Department of Defense structures having more stories are essential to consider PC. All DOD buildings with three or more stories are required to consider progressive collapse and its guideline can be assigned to reinforced concrete, wood, steel structures and structural components.

2.6.2 Guidelines of GSA

The General Service Administration guidelines, was particularly arranged to make sure that the risk of PC is considered in the construction, planning, and design of new federal office buildings and most important modernization projects. The subjects connected with the avoidance of PC should be considered throughout the reinforced concrete and steel buildings (GSA, 2003).

GSA guideline describes the evaluation process for PC, the loads to be used for the analysis and the acceptance criteria for progressive collapse. The issues associated with the avoidance of progressive collapse are considered for reinforced concrete and steel building structures (GSA, 2003).

2.7 Past Studies on Progressive Collapse

Houghton studied the beam to column connections are the hypotheses of the ALP method that give sufficient strength between beams transverse to a removed column (Houghton, 2000). When a column is removed, Crawford argues that a SidePlate™ system should be used to provide a solid connection across beams to prevent progressive collapse (Crawford, 2002). Hence, studies indicate that the use of side plates improves the rotational capacity of connection and hence energy dissipation aptitude that is useful for ALP and explosion loading scenarios (Houghton, 2000).

In 2002, Crawford explained that the use of trusses decreases the PC in high rise building. Protected ALP develops at columns on top of the removed column, if a column is removed within a segment. Then, these columns become tension elements that transfer floor loads to trusses above.

In 2008, Cheol-Ho Lee, Seonwoong Kim, Kyu-Hong, Kyungkoo Lee studied preliminary, two simplified analysis procedures but evaluation of PC potential in ductile welded steel moment frames. Nonlinear static PC analysis was then proposed

Jinkoo Kim and Taewan Kim (2008) studied the capacity of steel moment frames to resist PC. The linear static and nonlinear dynamic analysis procedures were applied. The results show that the PC potential of buildings with one column removal is more conservative when LS procedure is employed.

In 2012, R. Larijani assessed the two asymmetric steel framed buildings with different framing systems, steel sections and number of stories. Using the GSA linear static procedure and ETABS-3D software, he evaluated the buildings for PC potential. The comparison between the two cases showed that the implementation of the built-up steel box sections instead of the I-beam sections for the columns produced better results, as since the built-up box columns did not have a weak axis.

In 2012, S. Fadaei studied the progressive collapse of two regular (symmetric) types of steel framed buildings having floors of 9 m, 12 m and 15 m spans with I-beams and truss-beams. She investigated the effect of increasing span of I-beams and truss beams on the magnitude of PC of these buildings. The General Services Administration guidelines with linear static analysis procedure were used with ETABS computer program to carry out the analyses. The results indicated that, due to column removal, the vertical displacements and the potential of progressive collapse of truss beams are less than those of I-beams. In addition, buildings with 12 m and 15 m beam spans with truss beam floors have lower steel weight than those having I-beam floors. However, the case reverses when 9 m beam spans are used.

Research performed so far indicates that there is still need to investigate the PC potential of regular and irregular buidlings with truss beams and also to use non-linear analysis for these investigations. This thesis studied PC of regular and irregular steel framed buildings having floors with I-beams and truss beams. The GSA guidelines with linear and nonlinear static analyses procedures and ETABS software were used to carry out the analyses. The details of this study can be found in the following chapters of this thesis.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

The performance of PC for regular and irregular buildings were examined through computational analysis. ETABS software was used for the 3-D modelling and analysis of the buildings (ETABS 2013). The details of steel framed buildings and their structural members are presented in this chapter.

3.2 Description of the Regular Building

Regular Building means there is no removal of the structural members. The original model is maintained for all floors. The investigated structure is a steel framed building designed to be used as a dormitory building. It has five bays in the longitudinal direction (x-direction) and two bays in the transverse direction (y-direction). The building has eight stories. The typical bay widths are 6 m and 7.5 m in the y-direction and 6m in the x-direction. Each story has the same height of 3.30 m. The total height of the building is 26.4 m. The building has a braced frame with cross-bracing in the y-direction and moment frame with diagonal bracing to control lateral drift in x-direction. In addition to the self weight of the reinforced concrete floors, steel composite deck, 2.5 kN/m^2 additional dead load for finishes was assumed for typical floors. The live load was assumed to be 3.0 kN/m^2 for a typical floor. The details on regular buildings with I-beams and truss beams and properties of the steel sections are presented in the following sections 3.2.1 to 3.2.2.

3.2.1 Regular Building with I-Beam (RB-I)

In this case, I-beam sections were used as floor beams. The original model is maintained for all floors. In order to compare the results, analyses were carried out firstly for a Regular Building with I-beam. The analyses were carried out using two different analysis procedures for eight cases. First Linear static analysis was used for four cases and then these cases were also subjected to pushover analysis, which formed the other four cases. The first case was the removal of the column from the ground floor, short side of building. The second case was the removal of the column from the long side of building on gridline 1B (Gr1B) and gridline 1C (Gr1C), third case was removal of column from the corner of the building. Figures 3.1 to 3.4 show typical I-beam general 3-D view, plan layout, bracing elevation in y-direction and bracing elevation in x-direction, respectively, for the RB-I dormitory building.

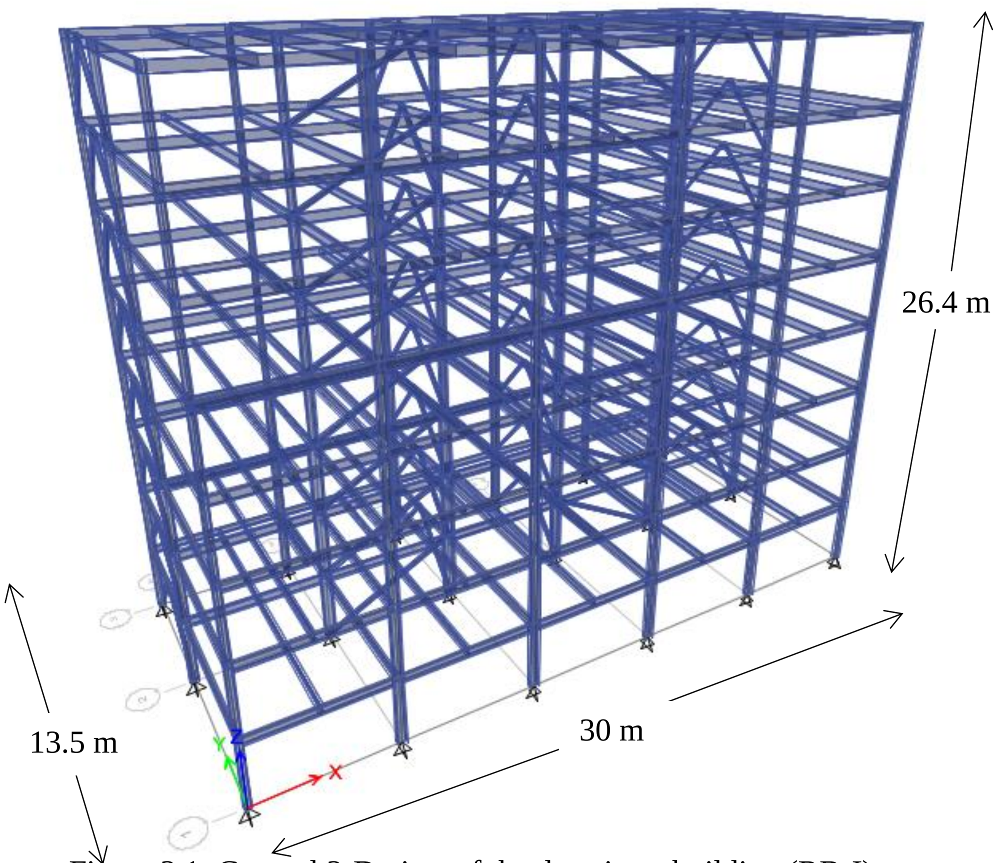

Figure 3.1: General 3-D view of the dormitory building (RB-I).

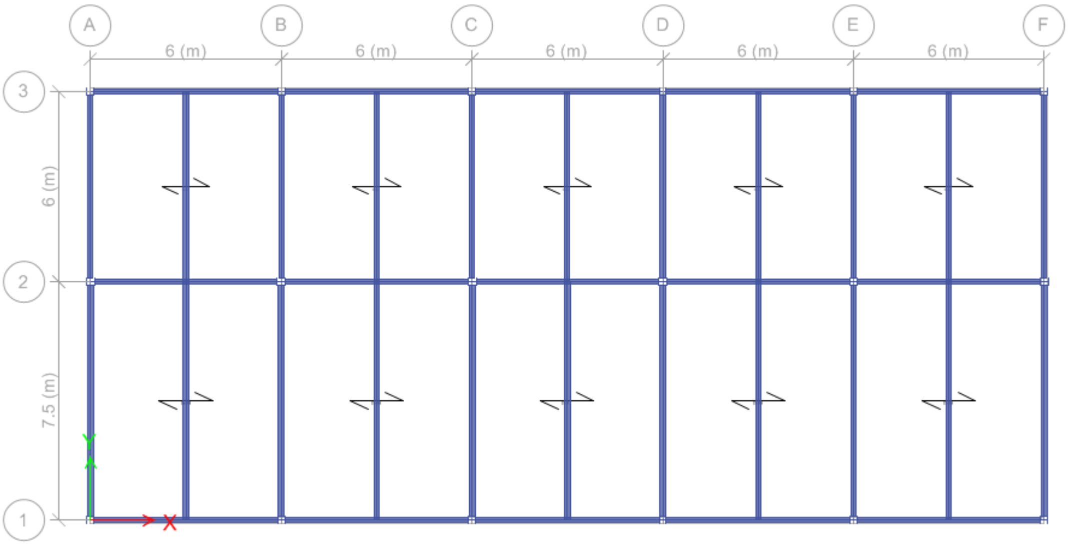

Figure 3.2: Typical floor plan fo the dormitory building (RB-I).

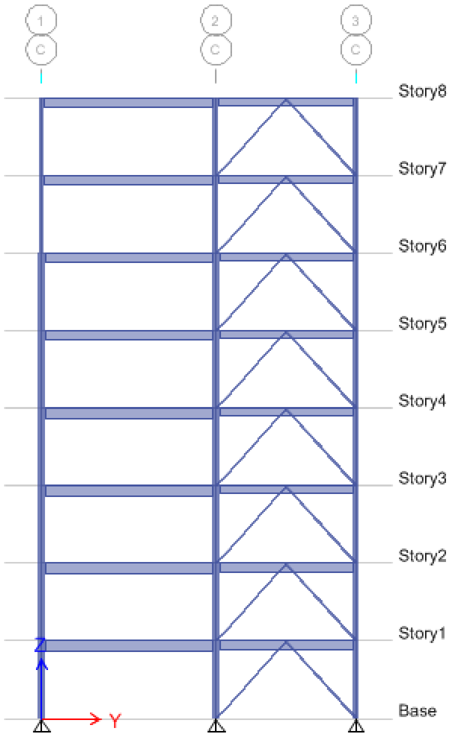

Figure 3.3: Typical I-beam and bracing elevation of the dormitory building (RB-I) in y-direction.

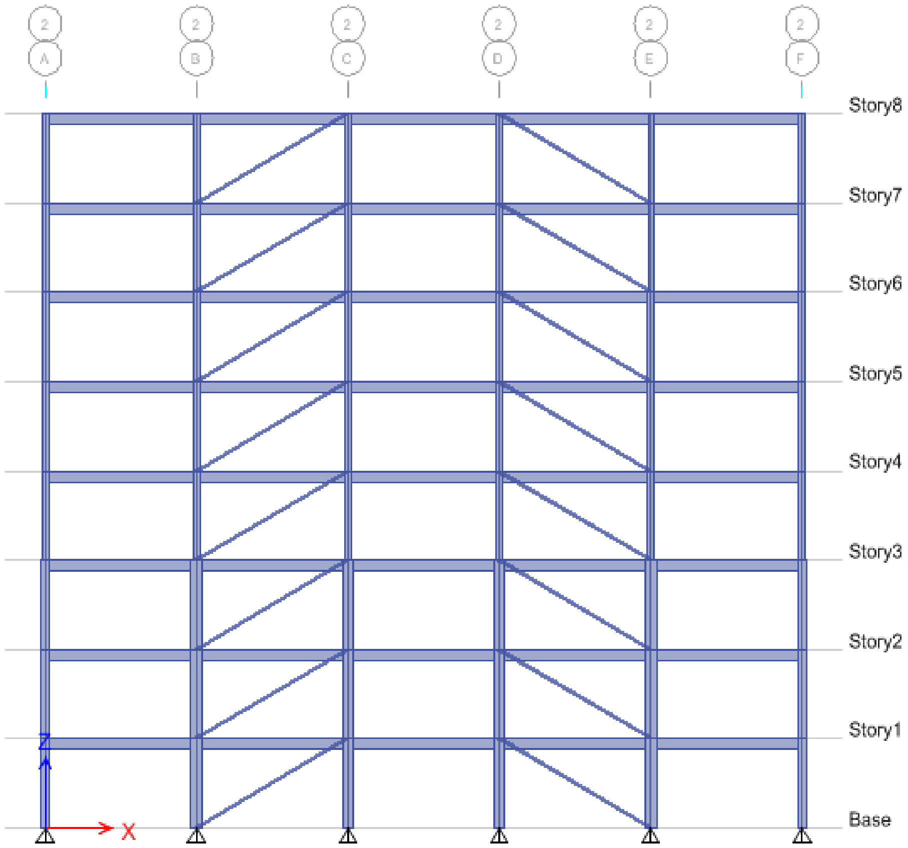

Figure 3.4: Typical I-beam and bracing elevation of the dormitory building (RB-I) in x-direction.

3.2.2 Regular Building with Truss Beam

In this case, truss beam made of hollow sections are used as floor beams. A truss is lightweight. The most beneficial system will be the one in which the flange forces are reduced to a minimum to save materials (Wisegeek, 2012). Similar to the buildings with I-beams two different analyses procedures were used, Linear static and nonlinear static, each with four cases. Hence, there were all together eight analysed cases for building with truss beam floors. Four column removal senarious, as explained for I-beam floors above, were used for each analysis procedure. The column was removed from the short side, long side (GR1B and Gr1C) and from the corner of the building. Figures 3.5 to 3.8 show typical truss beam general 3-D view, plan layout, bracing elevation in y-direction and bracing elevation in x-direction, respectively, for the RB-I dormitory building.The elevation given in Figure 3.7 was valid also for A and C axes.

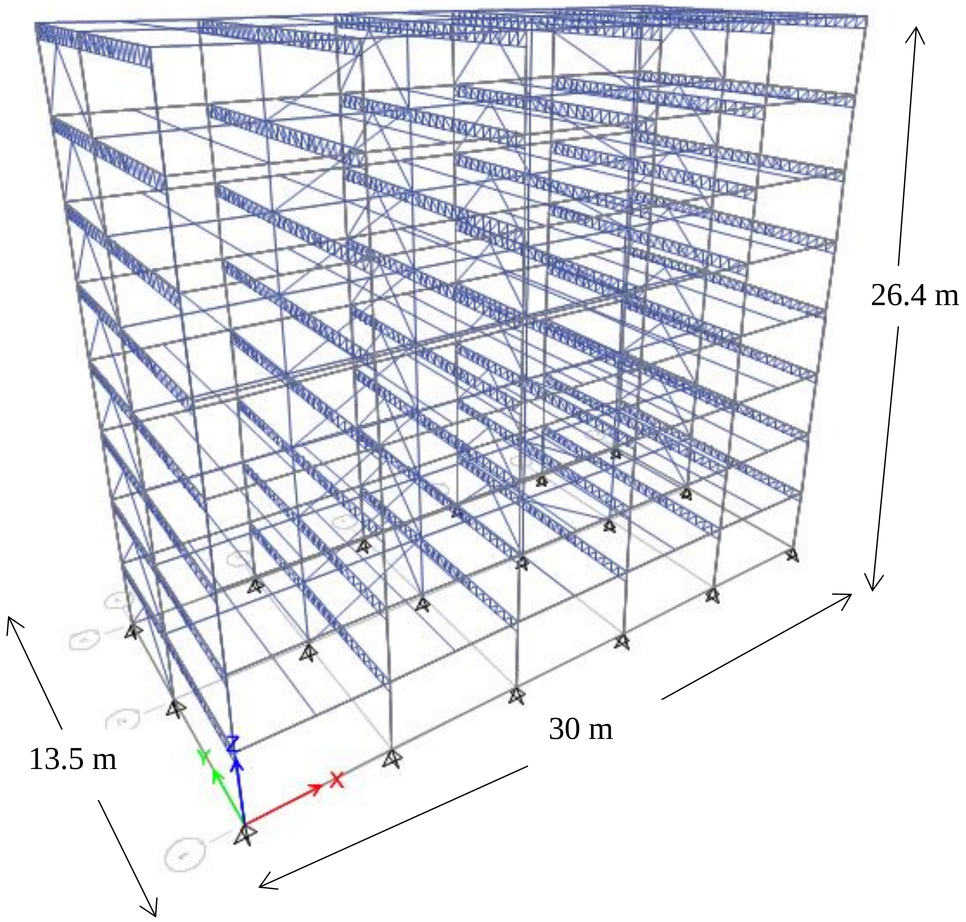

Figure 3.5: General 3-D view of the dormitory building (RB-T).

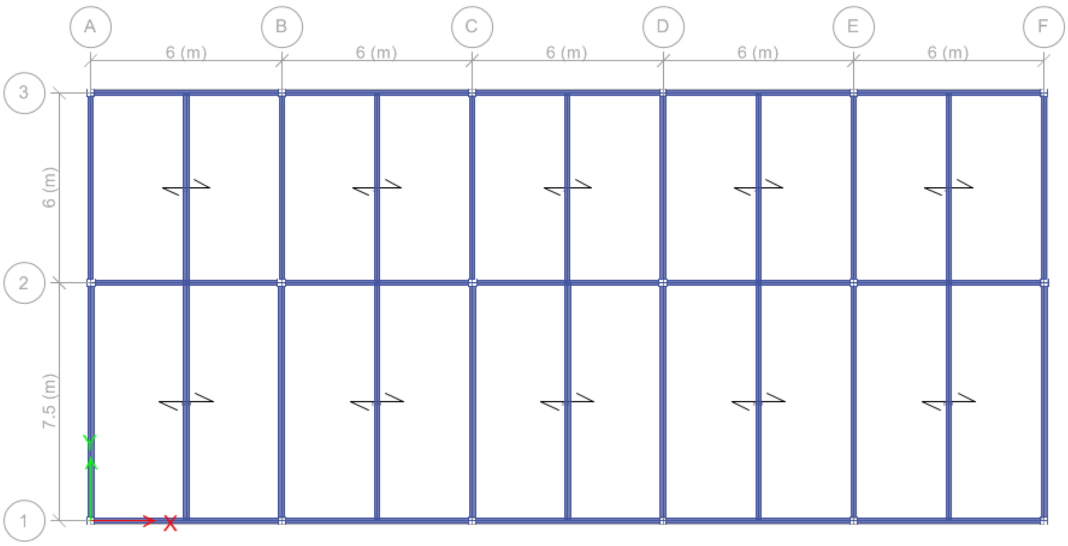

Figure 3.6: Typical floor plan of the dormitory building (RB-T).

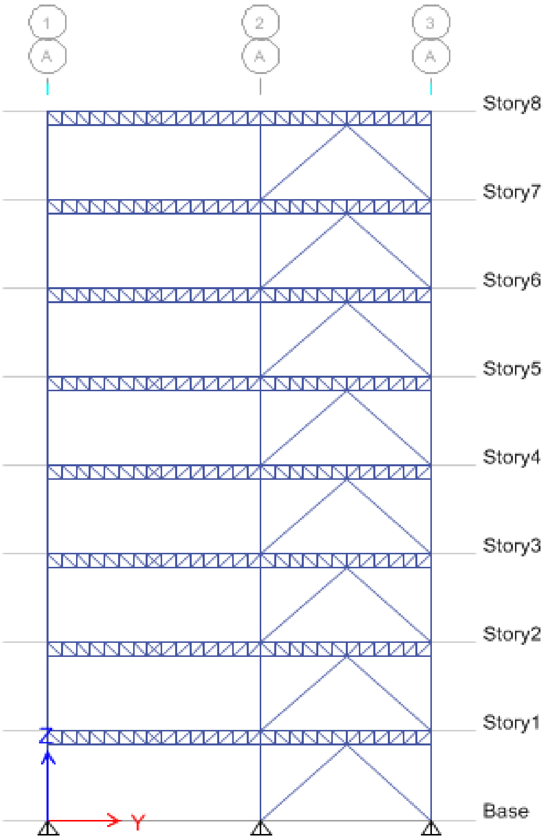

Figure 3.7: Typical truss beam and bracing elevation of the dormitory building (RB-T) in y-direction.

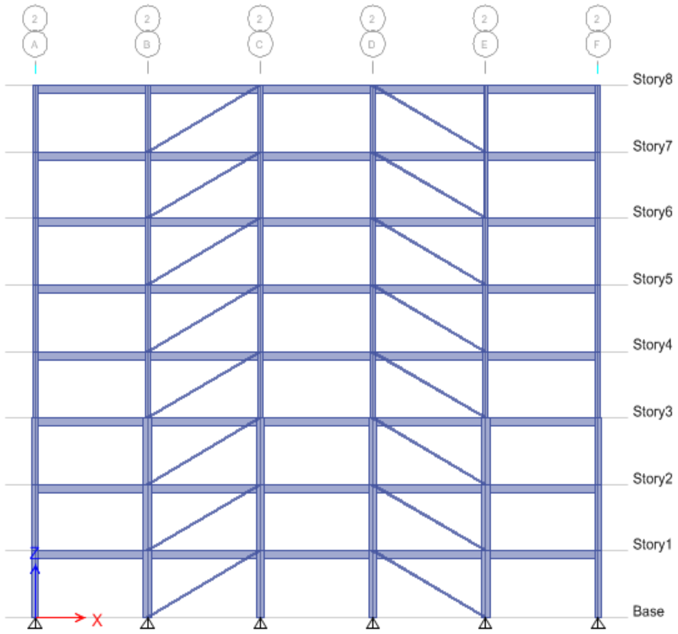

Figure 3.8: Typical truss beam and bracing elevation of the dormitory building (RB-T) in x-direction.

3.3 Description of the Irregular Building

Irregular Building indicates the removal of some of the floors from the building so that an irregularity is formed. Irregular frames with I-beam and truss beam floors are then subjected to two types of analysis procedures with four column removal scenarios creating some 32 different cases to analyse and use to compare the basic two types of buildings with I-beam and truss-beam floors. The properties of different cases and figures are presented in the following sections 3.3.1 to 3.3.2.

3.3.1 Irregular Buildings with I-Beam, IR8F-I and IR4F-I

IR8F and IR4F are the cases with removal of all eight or the first four floors from the ground level, between the gridlines 1-2/C-D, respectively. When each of these buildings were subjected to two types of analysis, with four column removal senarios, then this approach creates another 16 cases for determination of PC potential. In this case, I-beam sections are used for the floors. From here on the building models with I beams is referred to as ‘Irregular Buildings, IR8F-I and IR4F-I’. Four column removal scenarios, as explained in section 3.2.1 above for I-beam floors were used for each analysis procedure. The column was removed from the short side, long side (Gr1B and Gr1C) and from the corner of the building. Figures 3.9 to 3.12 show typical I-beam general 3-D view, plan layout, bracing elevation and bracing elevation at gridline 2, respectively, for the IR8F-I dormitory building.

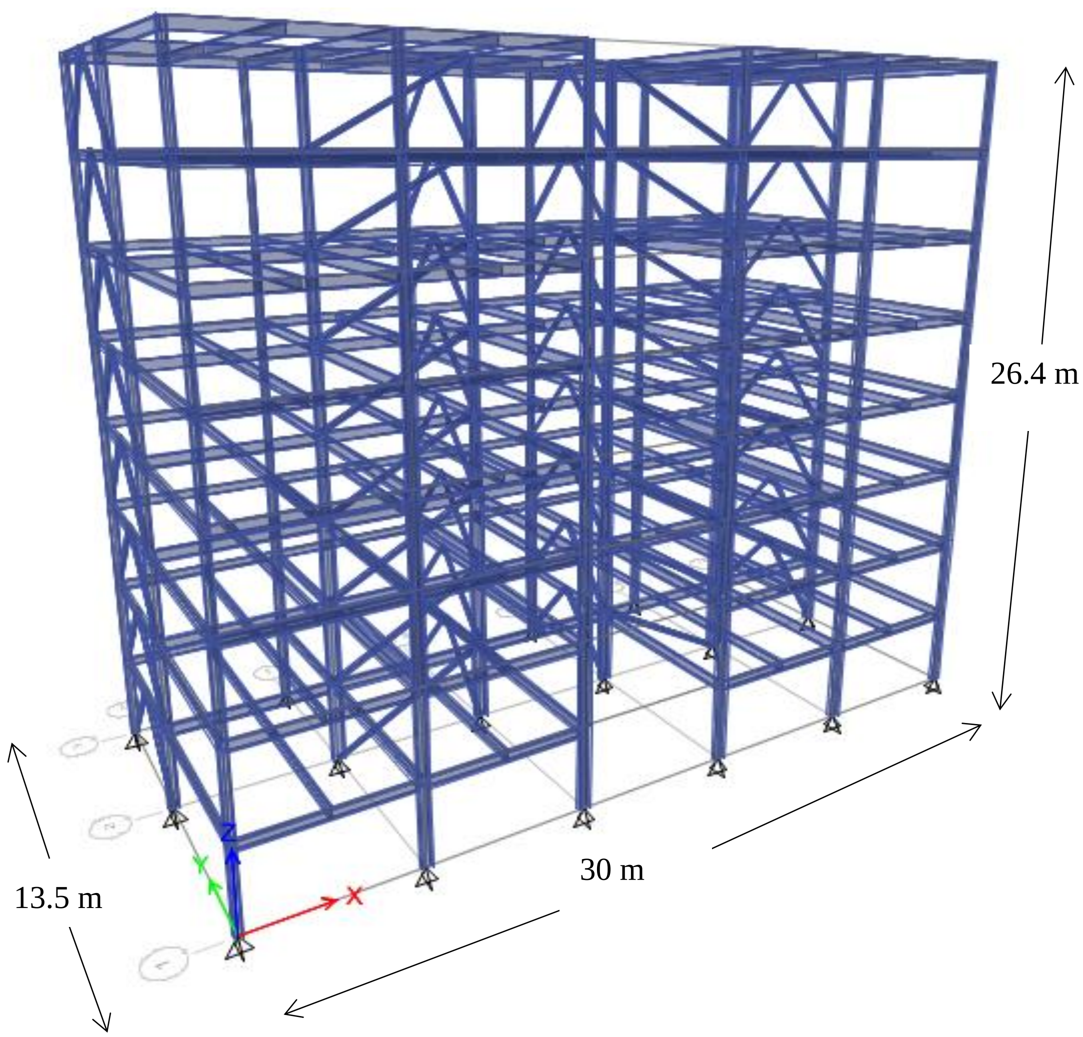

Figure 3.9: General 3-D view of the dormitory building (IR8F-I).

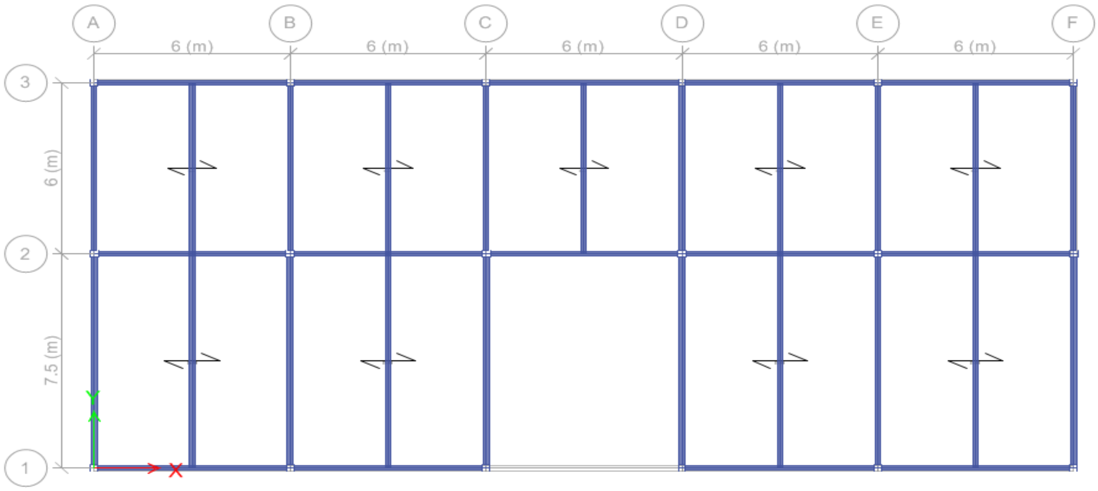

Figure 3.10: Typical floor plan of the dormitory building (IR8F-I).

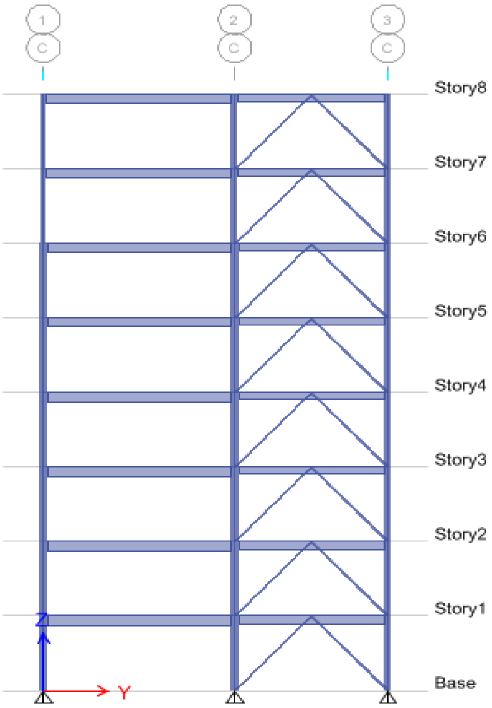

Figure 3.11: Typical I-beam and bracing elevation of the dormitory building (IR8F-I) in y-direction.

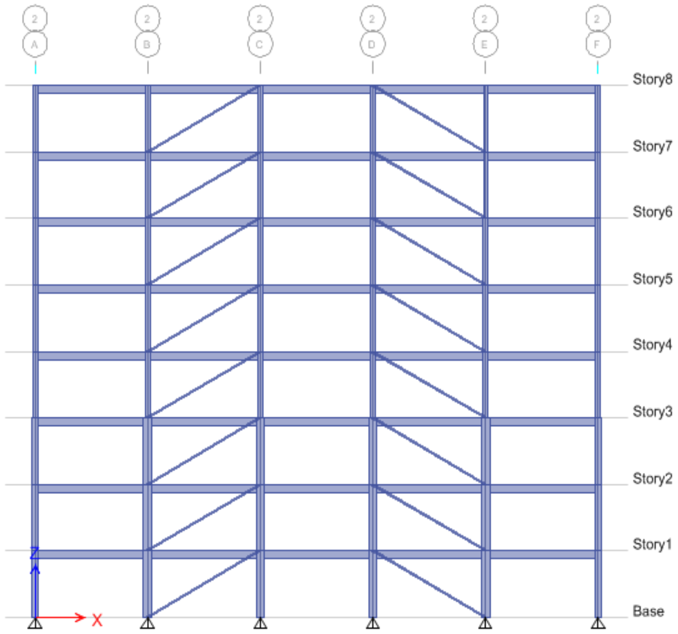

Figure 3.12: Typical I-beam and bracing elevation of the dormitory building (IR8F-I) in x-direction.

3.3.2 Irregular Buildings with Truss Beam, IR8F-T and IR4F-T

In this case, truss beams were used as floor beams. The rest of the information are same as those given for the irregular buildings with I-beam floors. Figure 3.13 shows general 3-D view of the dormitory,IR4F. Figures 3.14 to 3.16 show typical truss-beam general 3-D view, plan layout, bracing elevation and bracing elevation at gridline 2, respectively, for the IR4F-T dormitory building.

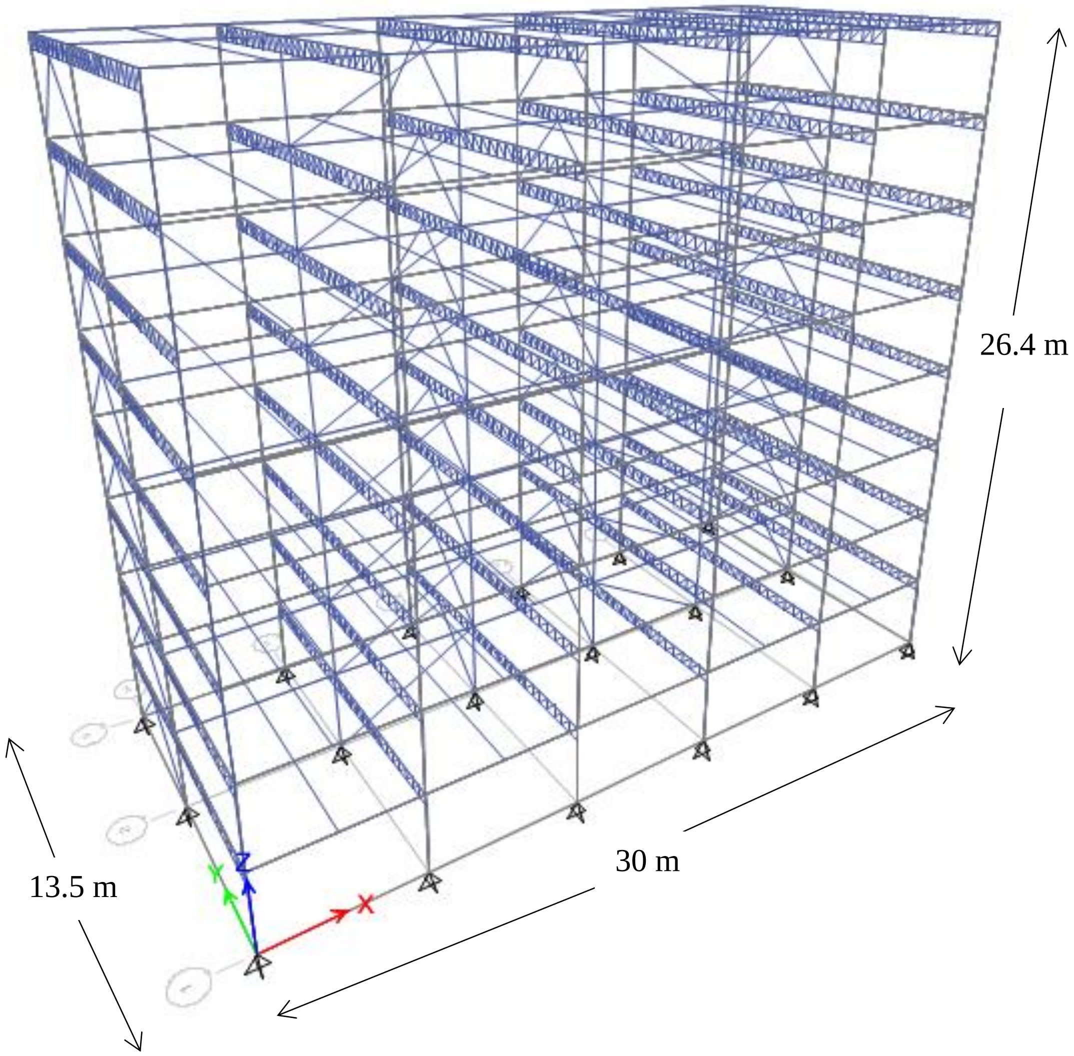

Figure 3.13: General 3-D view of the dormitory building (IR4F-T).

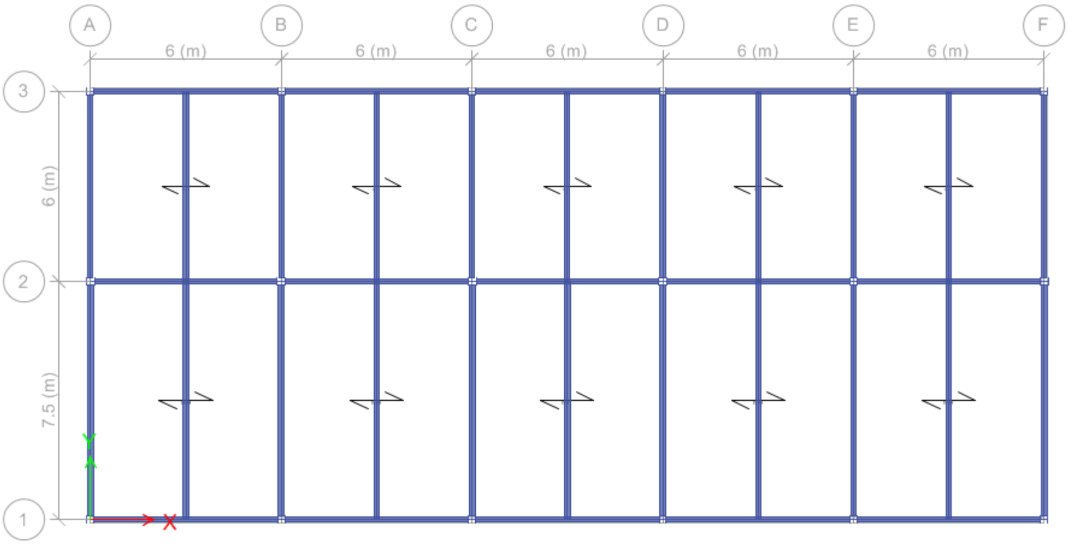

Figure 3.14: Typical floor plan of the dormitory building (IR4F-T).

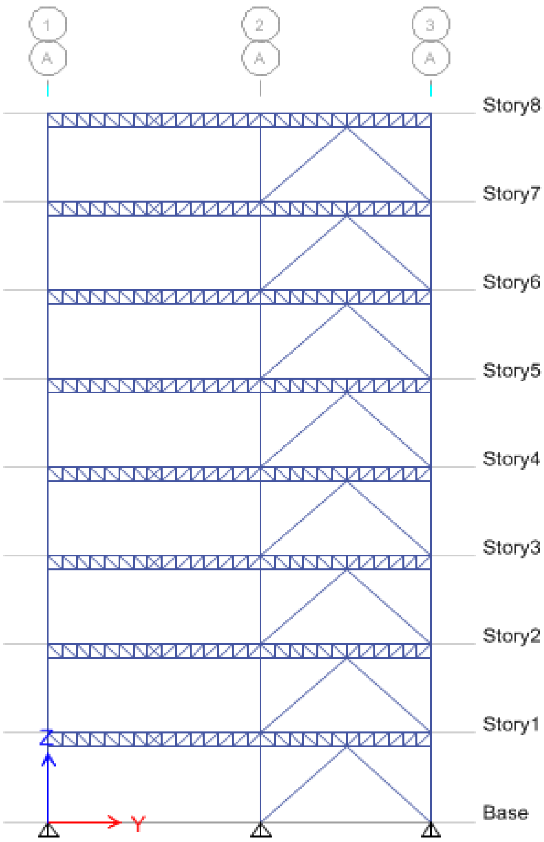

Figure 3.15: Typical truss-beam and bracing elevation of the dormitory building (IR4F-T) in y-direction.

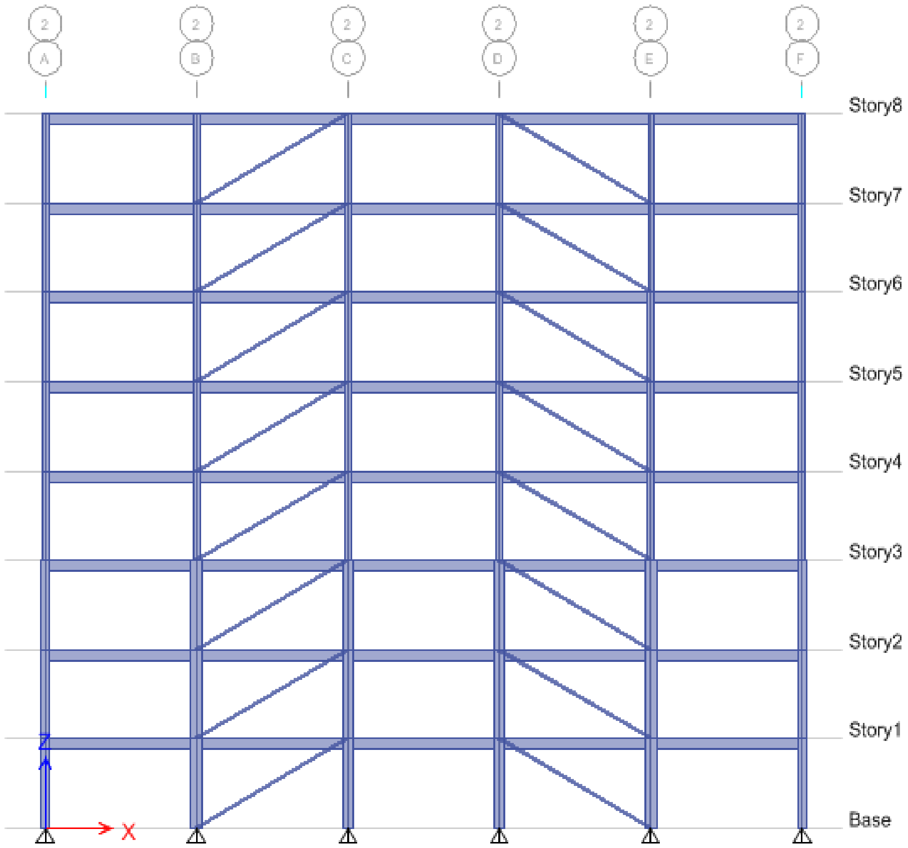

Figure 3.16: Typical truss-beam and bracing elevation of the dormitory building (IR4F-T) in x-direction.

3.4 Dimensions and Properties of Structural Members for Regular and Irregular Buildings

The properties of I-beams and columns are shown in Table 3.1 for regular, RB-I and irregular IR8F-I and IR4F-I buildings. In addition, the properties of steel truss beams and columns are shown in Table 3.2 for regular with truss-beam, RB-T and irregular, IR8F-T and IR4F-T buildings. The steel sections used for the structural members are given in Tables 3.1 and 3.2.

Table 3.1: Profile sections for RB-I, IR8F-I and IR4F-I

Column Sections	HE260B HE220B
Beam Sections	IPE360-IPE400-IPE330

Table 3.2: Profile sections for RB-T, IR8F-T and IR4F-T

Column Sections	HE260B HE220B
Beam Sections	IPE360-IPE400-IPE330
Truss Sections	
Top chord	IPE 100
Bottom chord	IPE120
Diagonal/Vertical	TUBO60x60x4

3.5 Material Properties

The model buildings used are regular and irregular steel framed structures with steel I-section columns and beams and truss beams used for the frame. Irrespective of whether the I-beam or truss beams are used as floor beams steel frame in y-direction is braced frame and the frame in x-direction is moment frame. Hence pinned (simple) and moment (rigid) beam-to-column connections were assumed for braced and moment frame, respectively. The truss internal members are assumed to be pinned to each other. S275 steel grade with a minimum yield strength of 250 N/mm^2 and modulus of elasticity of steel of 2 E+8 kN/m^{2}is used for all members of the steel framed building.

3.6 PC Analysis Procedures for Regular and Irregular Buildings

The linear and nonlinear static analysis steps for the complete analysis are described below. The most important methods of PC analysis is linear and nonlinear static methods. Linear analysis method is used only for first order theory (small displacement) building. The following steps for analyses are as shown in below:

1. Build a 3-Dimensional frame model using ETABS computer program.

2. Carry out linear static analysis and design the building and make sure that all the structural member DCR values are less than 2.0.

3. Choose the exterior frames with not low potential of PC.

4. According to General Services Administration guideline select linear static or nonlinear static analyses.

5. Apply the static load combination as defined in Eq (1) of GSA for linear static analysis / apply the static load combination as defined in Eq (3) of GSA for nonlinear static analysis.

6. Remove the column based on GSA guideline.

7. After removing the column, analyze the building.

8. Check DCR values for each element (beams, columns and bracings) for linear static analysis / rotation values for each element (beams, columns and bracings) for nonlinear static analysis.

9. Evaluate the results according to DCR values for LSA and rotation values for NLSA.

3.6.1 Loading Conditions for Linear Static Analysis (GSA, 2003)

The PC evaluating for every structural member in the structure, GSA recommended a common loading factor to be used for buildings. Accordingly, the recommended gravity loading conditions for LS analysis of a building, are as follows:

$$Load = 2(DL + 0.25LL) \qquad \text{Eq (1)}$$

Where, DL is the self-weight of the structure. In addition to the self weight of the reinforced concrete floors, steel composite deck of 2.5 kN/m^2 additional dead load for finishes was assumed for typical floors. The building was designed to be used as dormitory, hence, the LL of 3.0 kN/m^2 is taken as the live load.

In this study, one-way spanning, reinforced concrete slab composite with galvanized steel deck was considered for the floors.

3.6.1.1 Demand Capacity Ratio Acceptance Criteria

The Demand Capacity Ratio (DCR) for LS analysis procedure is based on Eq (2), as follows:

$$DCR = QUD / QCE \qquad \text{Eq (2)}$$

Where: QUD = Acting force (Demand). Determined or computed in element or connection/joint

QCE= Probable ultimate capacity (Capacity) of the component and/or connection/joint

Table 3.3 shows the General Services Administration particular Demand Capacity Ratio (DCR) limits for steel frame section. The members are considered to be failed if structural members with DCR values exceed those given in Table 3.3 (GSA, 2003).

DCR < 2.0: for typical structural configuration

DCR < 1.5: for atypical structural configuration

Cases which were chosen for this study have typical structural configuration. Table 3.3 explains the acceptance criteria of GSA DCR for the steel buildings. Hence, in theory, a Demand Capacity Ratio rate of > 2.0 indicates the member being exceeded its ultimate capacity.

Table 3.3: GSA specified DCR acceptance criteria for the steel building (GSA, 2003).

Component/Action	**Values for Linear Procedures DCR**
Columns – flexure	
For $0 < P/PC_L < 0.5$	
a. $\frac{b_f}{2t_f} \leq \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \leq \frac{260}{\sqrt{F_{ye}}}$	2
b. $\frac{b_f}{2t_f} \geq \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \geq \frac{460}{\sqrt{F_{ye}}}$	1.2
For $P/PC_L > 0.5$	
a. $\frac{b_f}{2t_f} \leq \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \leq \frac{300}{\sqrt{F_{ye}}}$	1
b. $\frac{b_f}{2t_f} \geq \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \geq \frac{400}{\sqrt{F_{ye}}}$	1
Beams – flexure	
a. $\frac{b_f}{2t_f} \leq \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \leq \frac{418}{\sqrt{F_{ye}}}$	3
b. $\frac{b_f}{2t_f} \geq \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \geq \frac{640}{\sqrt{F_{ye}}}$	2

b_f = Width of the compression flange
t_f = Flange thickness
F_{ye} = Expected yield strength
h = Distance from inside of compression flange to inside of tension flange
t_w = Web thickness
PC_L = Lower bound compression strength of the column
P = Axial force in member taken as Q_{uf}

3.6.2 Loading Conditions for Nonlinear Static Analysis

When compared with LS the NLS analysis is a more sophisticated approach. Hence, it would take considerably more time to carry out analysis and design for buildings. GSA (2003) recommended the use of a common loading factor for evaluating the PC of every structural member in the buildings. For the NLSA of a building, GSA recommends the use of the gravity loading as follows:

$$Load = (DL + 0.25LL) \quad \text{Eq (3)}$$

DL = self-weight of slab and its floor finishes.

Hence the floor finishes and floor live loads were assumed as 2.5 kN/m^2 and 3.0 kN/m^2 since the building was designed to be used as a dormitory.

3.6.2.1 Acceptance Criteria for Nonlinear Analysis

NLS can be used to find the damage level of a Structure and it uses acceptance criteria that is less restrictive . Table 3.4 provides the maximum allowable ductility and rotation limits for many structural components to limit the possibility of progressive collapse.

Table 3.4: Acceptance criteria for nonlinear analysis[1] extracted from Table 2.1 of (GSA,2003).

COMPONENT	DUCTILITY (μ)	ROTATION Degrees (θ)[2]	ROTATION %Radian (θ)[2]
Steel Beams	20	12	21
Metal Stud Walls	7		
Open Web Steel Joist (based on flexural tensile stress in bottom chord)	6		
Metal Deck	20	12	21
Steel Columns (tension controls)	20	12	21
Steel Columns (compression controls)	1		
Steel Frames		2	3.5
Steel Frame Connections; Fully Restrained			
• Welded Beam Flange or Coverplated (all types)		1.5	2.5
• Reduced Beam Section		2	3.5
Steel Frame Connections; Proprietary		2 to 2.5	3.5 to 4.5
Steel Frame Connections; Partially Restrained			
• Limit State governed by rivet shear or flexural yielding of plate, angle or T-section		1.5	2.5
• Limit State governed by high strength bolt shear, tension failure of rivet or bolt, or tension failure of plate, angle or T-section		1	1.5

Notes:
1. COTR approval must be obtained for the use of updated tables.
2. Proprietary connections must have documented test results justifying the use of higher rotational limits.
3. Rotation for members or frames can be determined using Figures 3.17 and 3.18 provided below.

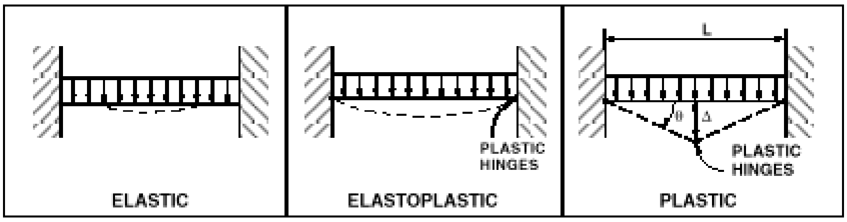

Figure 3.17: Measurement of (θ for) after mation of plastic hinges. (GSA,2003).

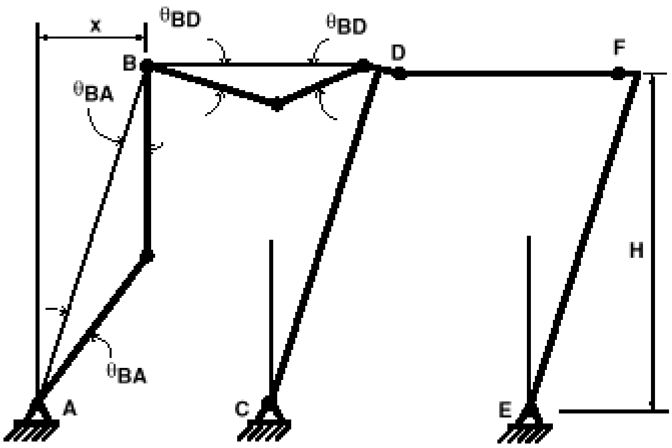

Figure 3.18: Sidesway and member end rotations (θ) for frames (GSA,2003).

3.7 Column Removal Procedure (GSA (2003))

This procedure includes removal of a column from the first storey, near middle of the short side, near middle of the long side and from the corner of the building, successively. The PC analysis demanded for the framed structures and the limitation of the collapse areas of buildings are shown in Figures 3.19 and 3.20, respectively.

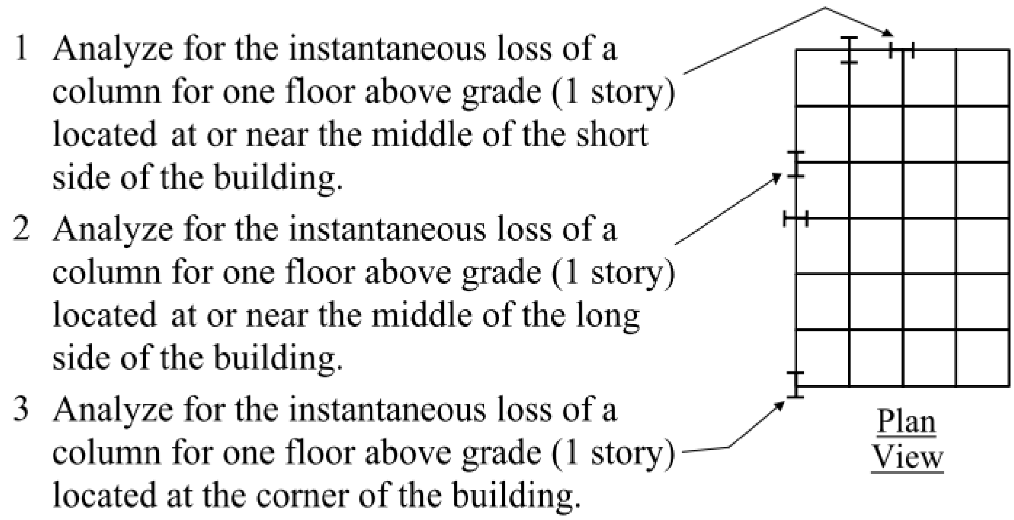

Figure 3.19: Progressive Collapse Analysis required for the framed structure (GSA, 2003).

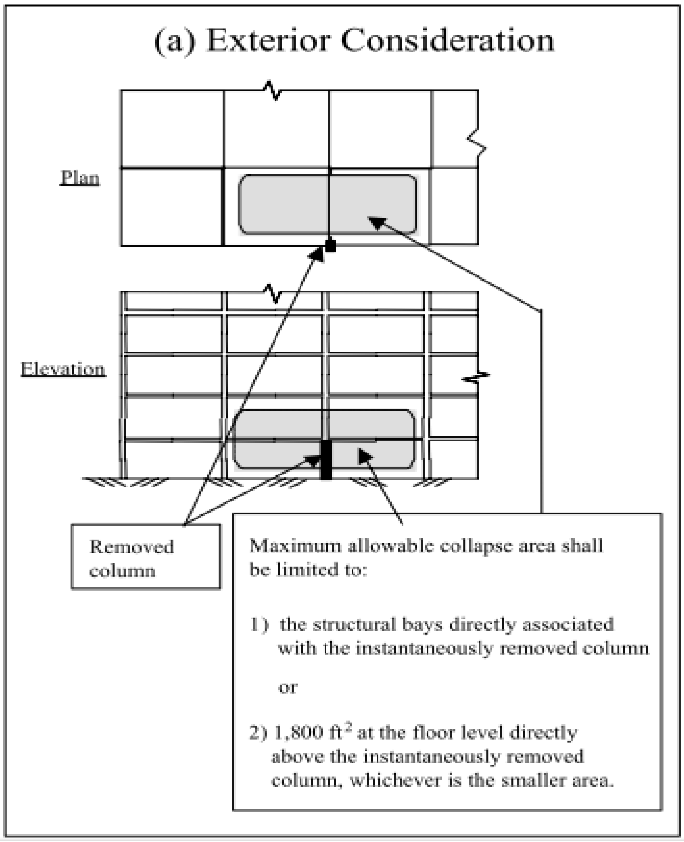

Figure 3.20: Limitation of collapse areas of structure supported by the columns (GSA, 2003).

Chapter 4

RESULTS AND DISCUSSIONS FOR LINEAR STATIC ANALYSIS

4.1 Introduction

In this chapter, results of the PC analysis, values of DCR for beams and columns are presented. Also rehabilitation of the members with high PC potential were carried out.

4.2 Regular Buildings, (RB)

The column removal locations are given in Figure 4.1.

- Case1: column was removed from gridline 2A, short side,
- Case2: column was removed from gridline 1B-, long side
- Case3: column was removed from gridline 1C, long side
- Case4: column was removed from the corner, gridline 1F.

DCRs for the steel frames with I-Beams are given in Figures 4.2 to 4.5 and those DCRs for steel frames with truss beams are given in Figures 4.6 to 4.9.

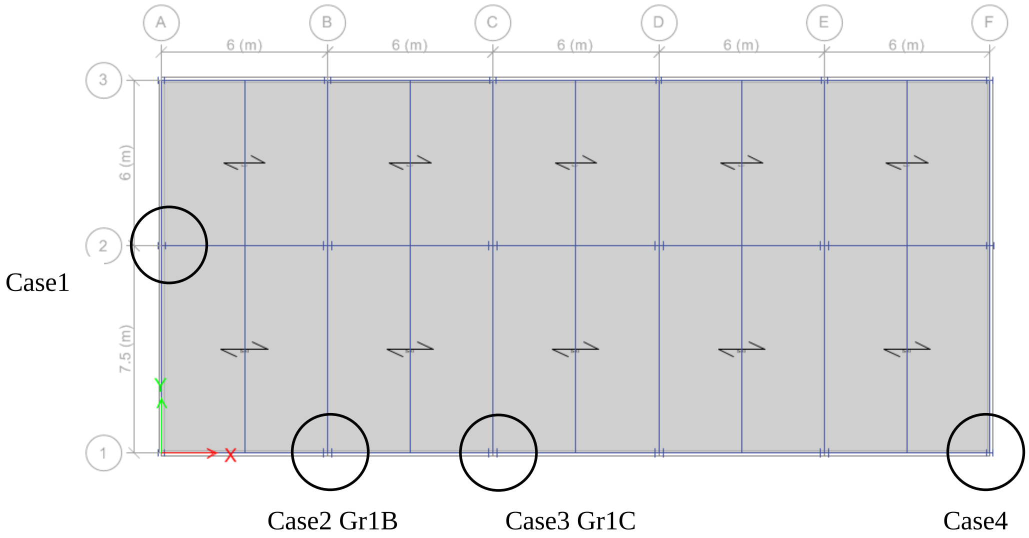

Figure 4.1: The locations of columns to be removed based on GSA guideline (RB).

4.2.1 PC Potential of Regular Building with I-Beams, (RB-I)

Figure 4.2 shows that none of the DCR value is more than 2.0. Therefore, according to GSA there is no potential of PC due to the removal of a column. In Figures 4.3 to 4.5, some of the members achieved values of DCR> 2.0 which is above accepted limits. Hence, this case leads to the increase in the potential of PC.

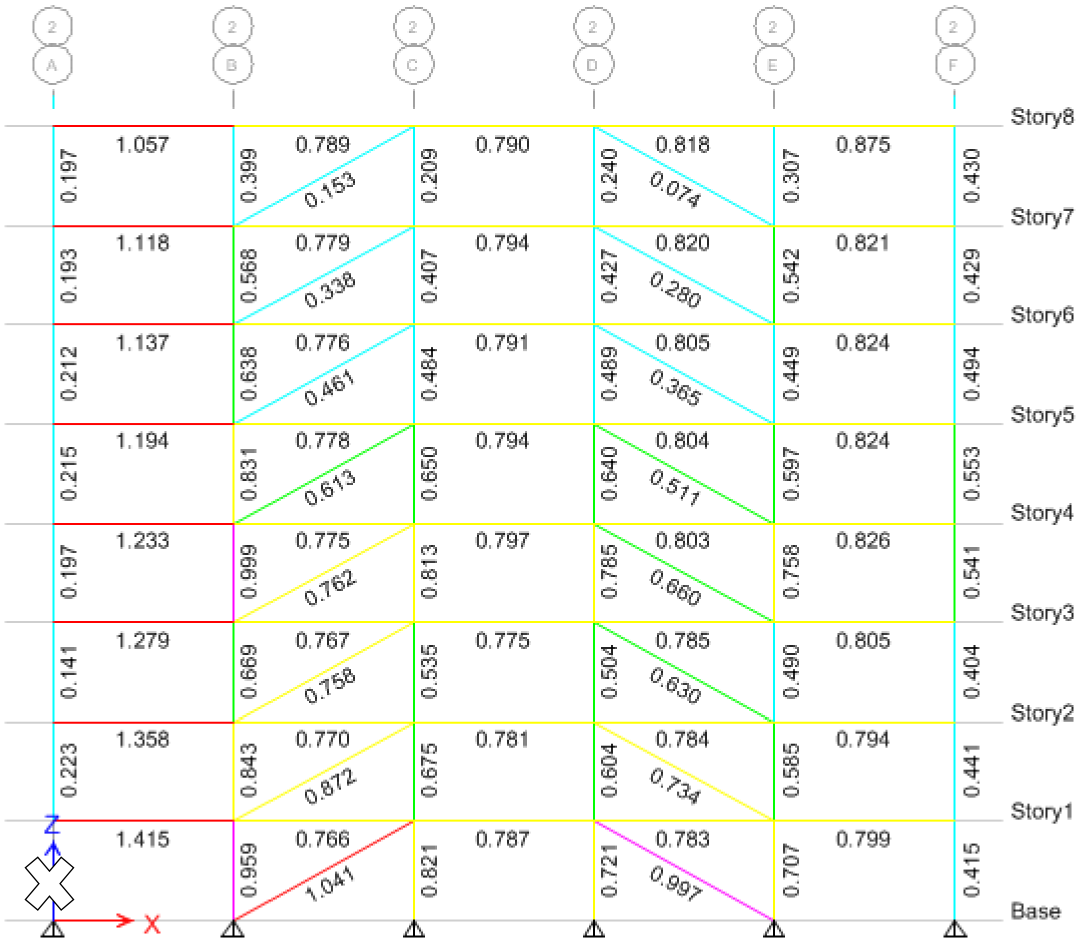

Figure 4.2: DCRs for RB-I Case 1 - column is removed from the short side of the building.

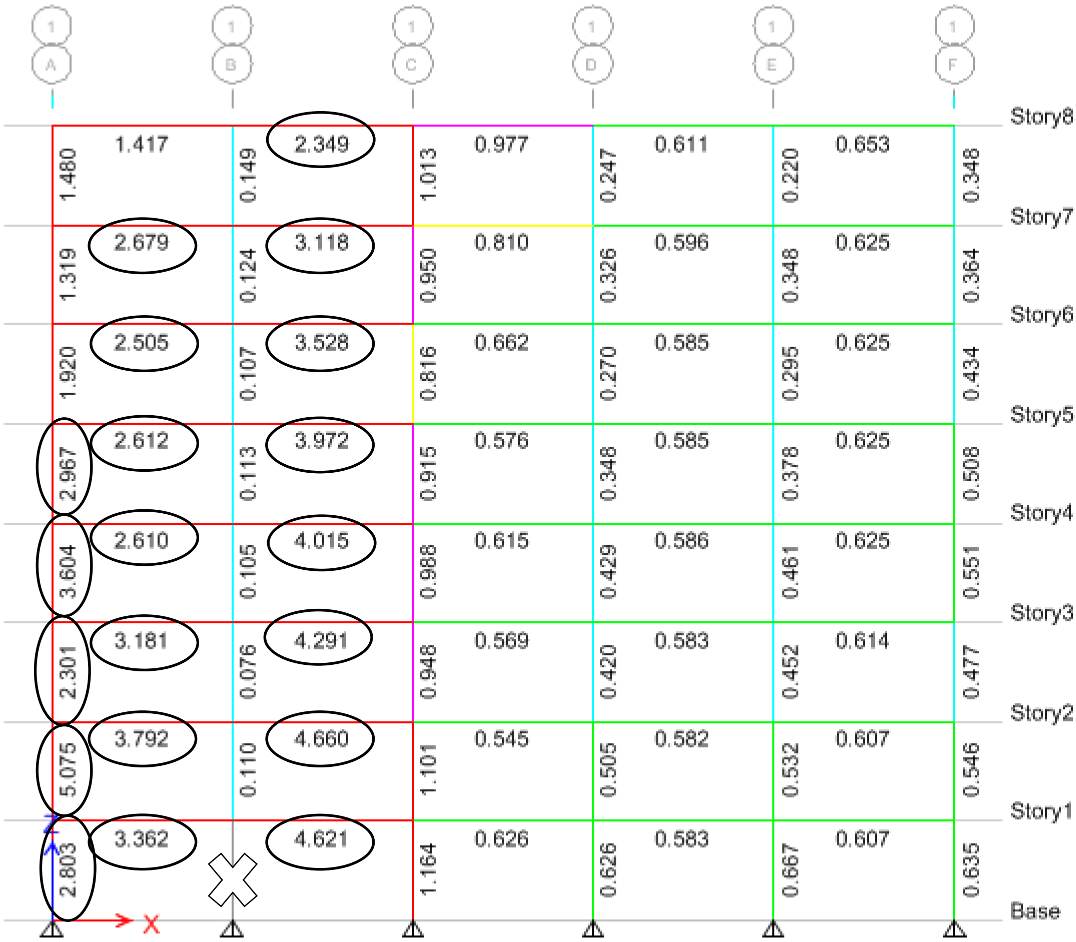

Figure 4.3: DCRs for RB-I Case 2 - column is removed from the long side (Gr1B) of the building.

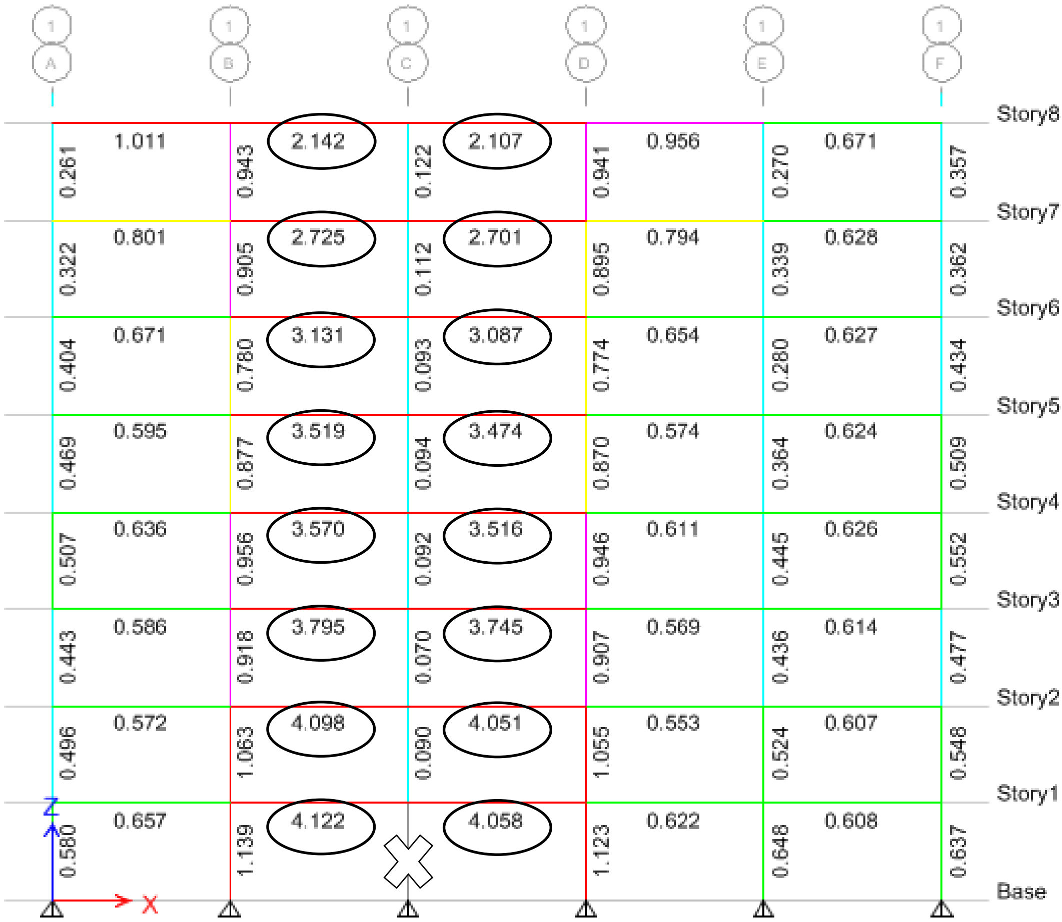

Figure 4.4: DCRs for RB-I Case 3 - column is removed from the long side (Gr1C) of the building.

Figure 4.5: DCRs for RB-I Case 4 - column is removed from the corner of the building.

4.2.2 PC Potential of Regular Building with Truss Beams, (RB-T)

In this section, the Demand Capacity Ratio's were calculated for Regular Building, then compared with each element of the building with truss beams. Figure 4.6 indicate that none of the values of DCR is more than 2.0. Therefore, there is no risk of PC. As can be seen in Figures 4.7 to 4.9, some of the members achieved DCR>2.0 which leads to increased risk of PC.

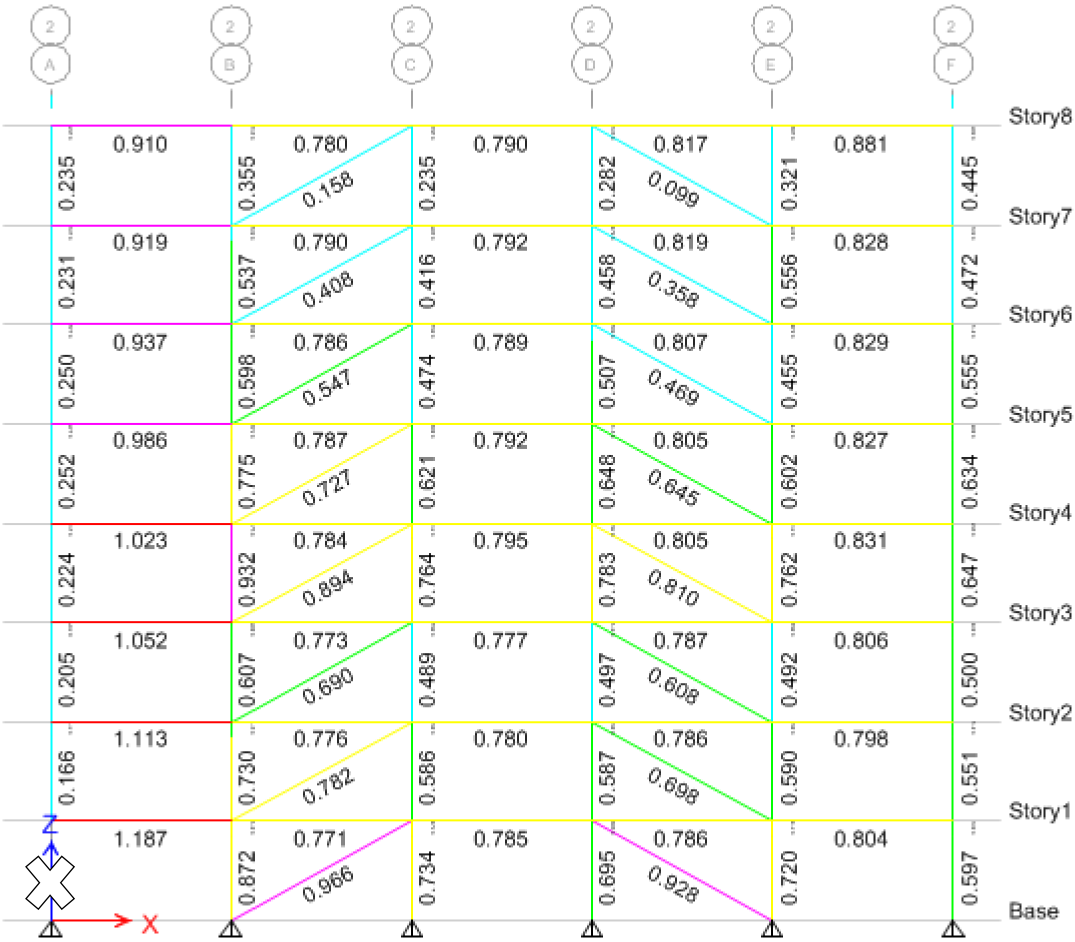

Figure 4.6: DCRs RB-T Case 1 - column is removed from the short side of the building.

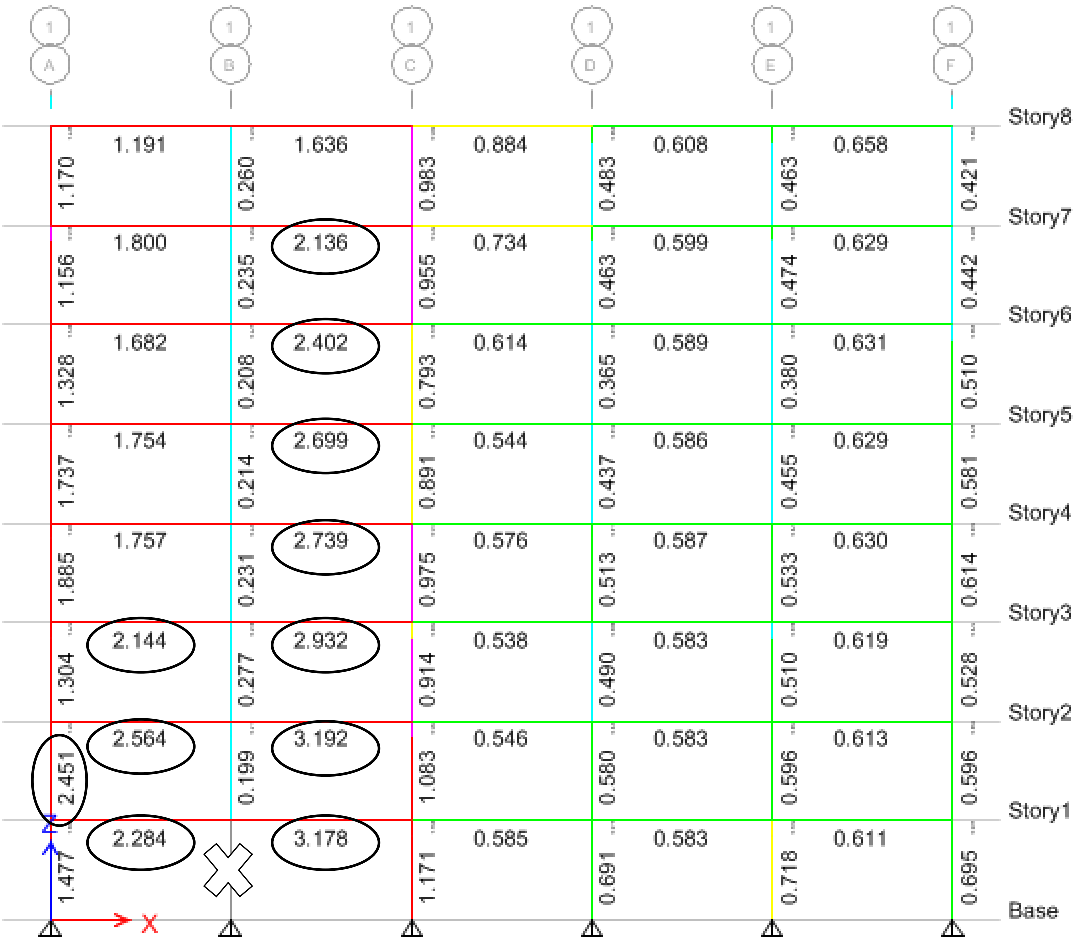

Figure 4.7: DCRs RB-T Case 2 - column is removed from the long side (Gr1B) of the building.

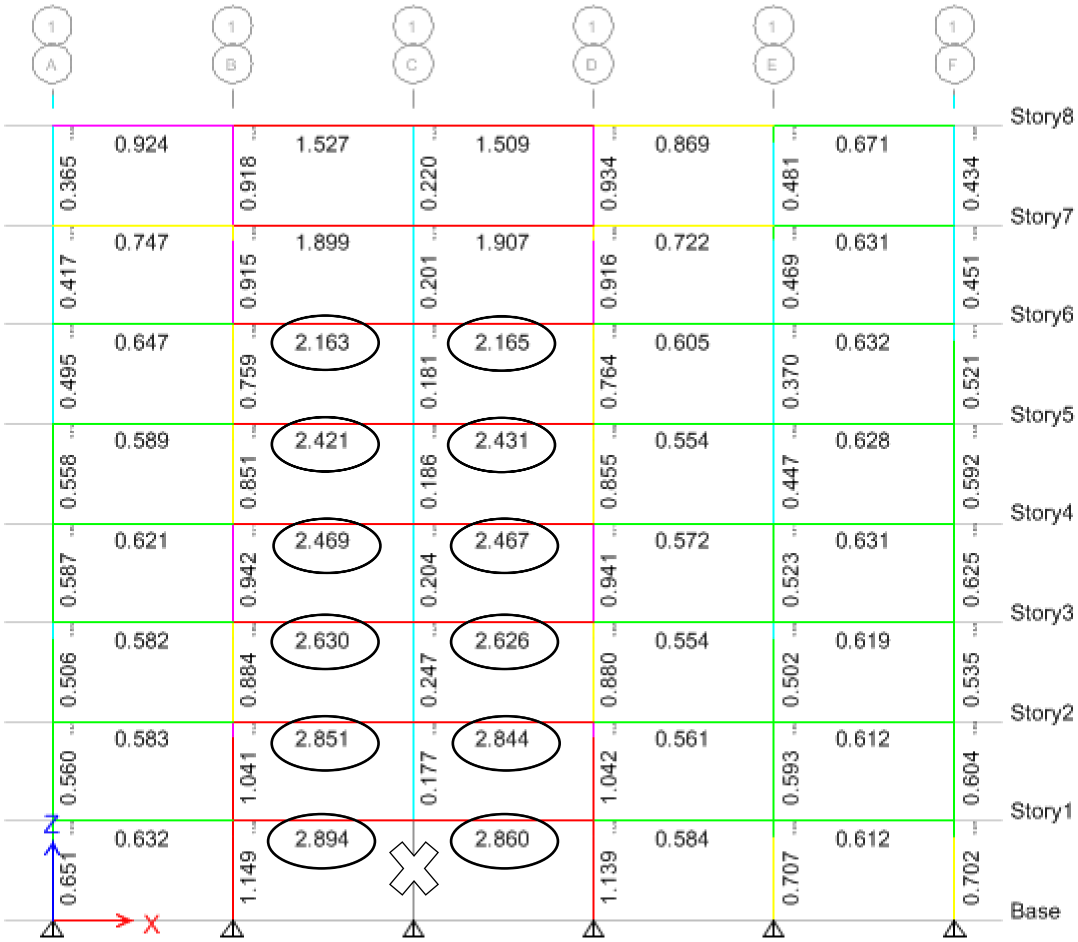

Figure 4.8: DCRs RB-T Case 3 - column is removed from the long side (Gr1C) of the building.

Figure 4.9: DCRs RB-T Case 4 - column is removed from the corner of the building.

Comparing the DCR values for RB-I and RB-T, the DCR values for I-beams are more than the top and bottom chords of truss beams. Therefore, according to GSA guideline, when a column is suddenly removed, the building with a lower DCR value is safer. Hence, overall the PC potential of the building with truss beams is less than the one with I-beams.

4.3 Irregular Buildings, (IR8F)

Figure 4.10 explained the cases established for the removal of each column. Case 1, 2,3 and 4 are the removal of the column from the short side, long side and corner of the building, respectively. Demand Capacity Ratios were calculated, then compared for each element of the building with I-beams and truss beams for 8 Floors Irregular Building (IR8F).

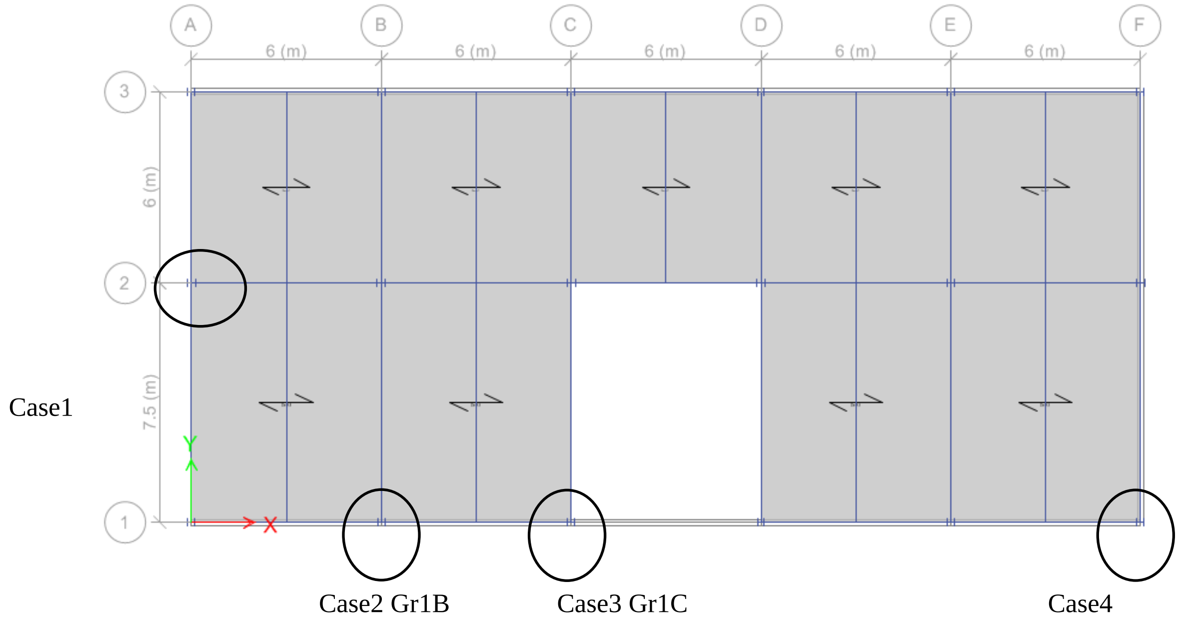

Figure 4.10: The locations of columns to be removed based on GSA guideline (IR8F).

4.3.1 PC Potential of IR8F Building with I-Beams, (IR8F-I)

Demand Capacity Ratio's calculated for 8 Floors Irregular Building, then compared for each element of the building with I-beams in this section. Figure 4.11 indicates no risk of PC for as a result of column removal from the short side of the building. All DCRs are less than 2.0. However, removing first story column from the corner and long side of the building caused DCR values exceeding the accepted limits (Figures 4.12 to 4.14).

Figure 4.11: DCRs IR8F-I Case 1 - column is removed from the short side of the building.

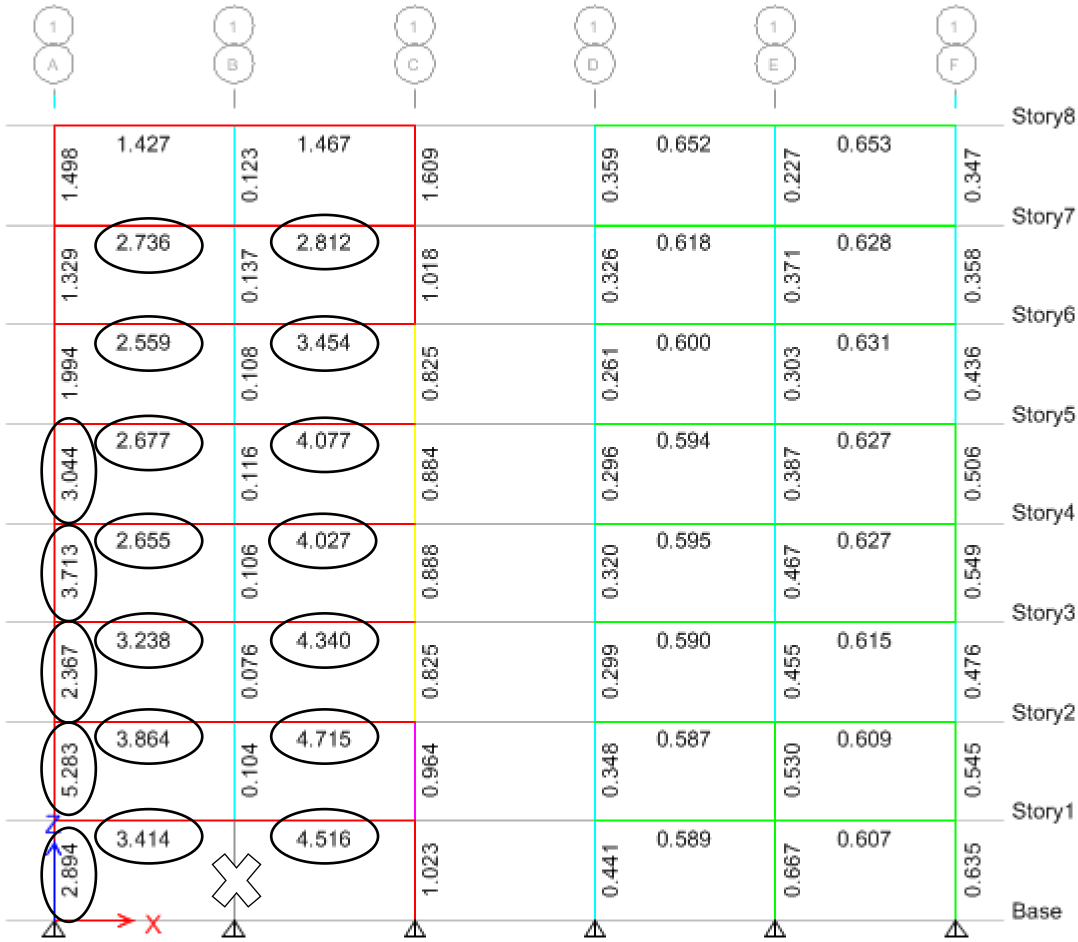

Figure 4.12: DCRs IR8F-I Case 2 - column is removed from the long side (Gr1B) of the building.

Figure 4.13: DCRs IR8F-I Case 3 - column is removed from the long side (Gr1C) of the building.

Figure 4.14: DCRs IR8F-I Case 4 - column is removed from the corner of the building.

4.3.2 PC Potential of IR8F Building with Truss Beams, (IR8F-T)

Demand Capacity Ratio's calculated for 8 Floors Irregular Building, then compared for each element of the building with truss beams in this section. Figure 4.15 indicates no risk of PC for as a result of column removal from the short side of the building. All DCRs are less than 2.0. However, removing first story column from the corner and long side of the building caused some of the DCR values to exceed the accepted limits (Figures 4.16 to 4.18). Hence the potential of PC is high.

Figure 4.15: DCRs IR8F-T Case 1 - column is removed from the short side of the building.

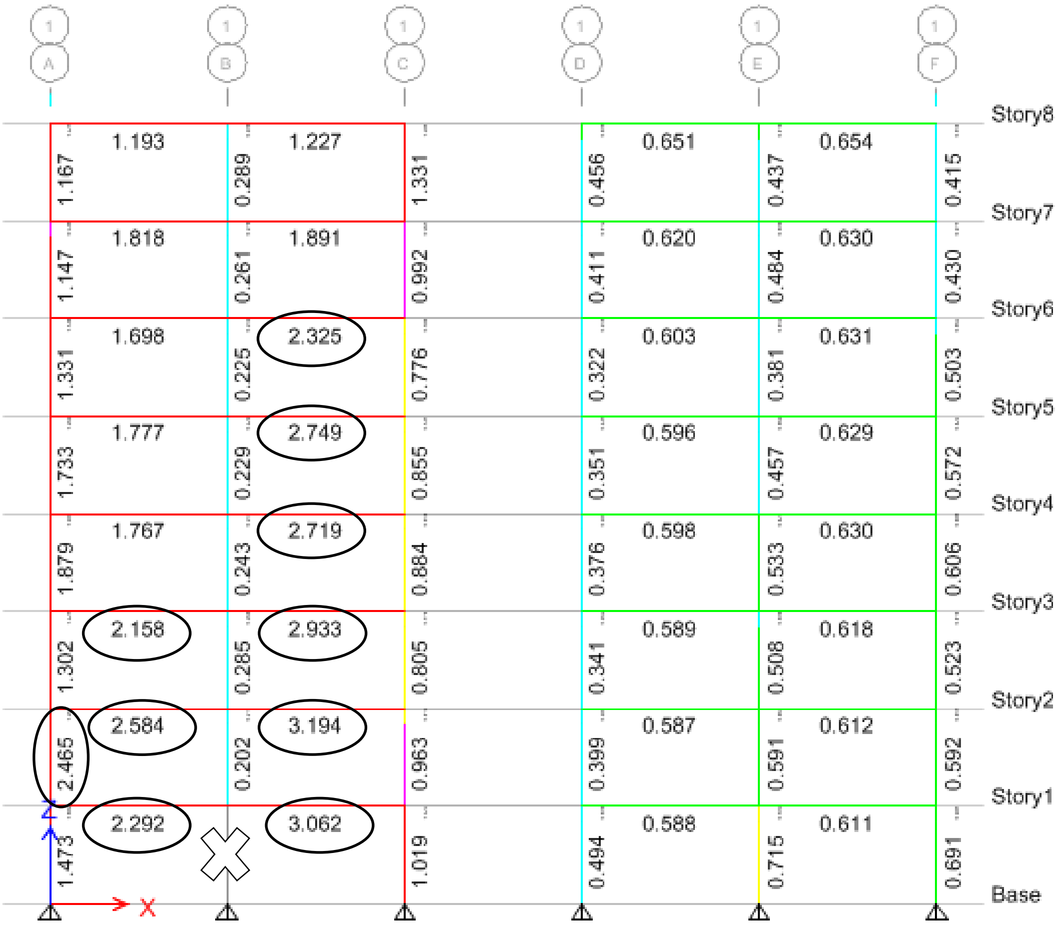

Figure 4.16: DCRs IR8F-T Case 2 - column is removed from the long side (Gr1B) of the building.

Figure 4.17: DCRs IR8F-T Case 3 - column is removed from the long side (Gr1C) of the building.

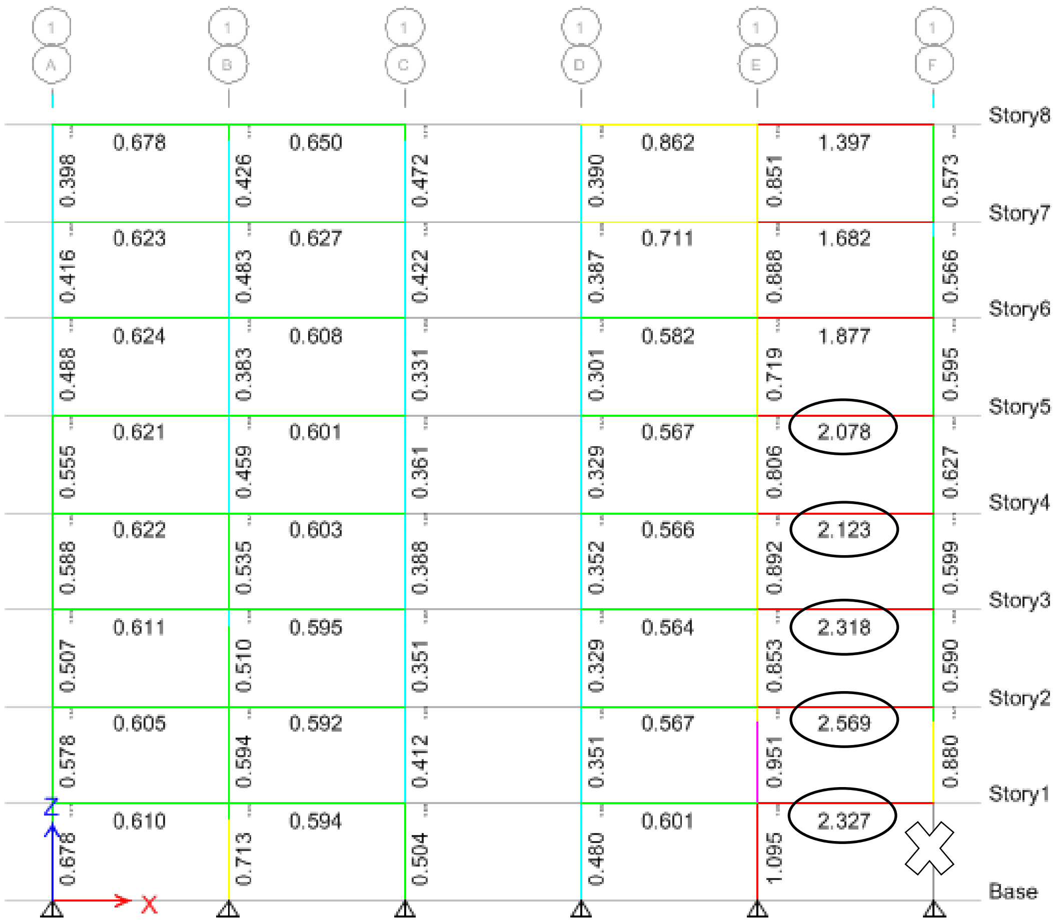

Figure 4.18: DCRs IR8F-T Case 4 - column is removed from the corner of the building.

Comparing the DCR values for IR8F-I and IR8F-T, the DCR values for I-beams are more than the top and bottom chords of truss beams. Therefore, when a column is suddenly removed, the building achieving a DCR value less than the stated limits would be safer than the one with a high DCR value (GSA, 2003). In addition, truss beam behaves better than I-beams. In 2012, S. Fadaei studied PC of steel framed structures having floors with I-beams and truss beams. The results showed that the vertical displacements and the potential of PC of I-beams are more than the truss beams due to one column removal.

4.4 Irregular Buildings, (IR4F)

Comparing the DCR values for IR4F-I and IR4F-T, the DCR values for I-beams are more than the top and bottom chords of truss beams. The structure with a lower Demand Capacity Ratio values is safer than the one with high Demand Capacity Ratio value when a column is suddenly removed. In addition, building with truss beams achieved a better behavior than the one with I-beams.

Well known column removal cases are given in Figure 4.19. Case 1, 2, 3 and 4 are the removals of columns from the short side, corner and long side of the building. Demand Capacity Ratio’s calculated, then compared with each element of the building with I-beams and truss beams for 4 floors irregular buildings.

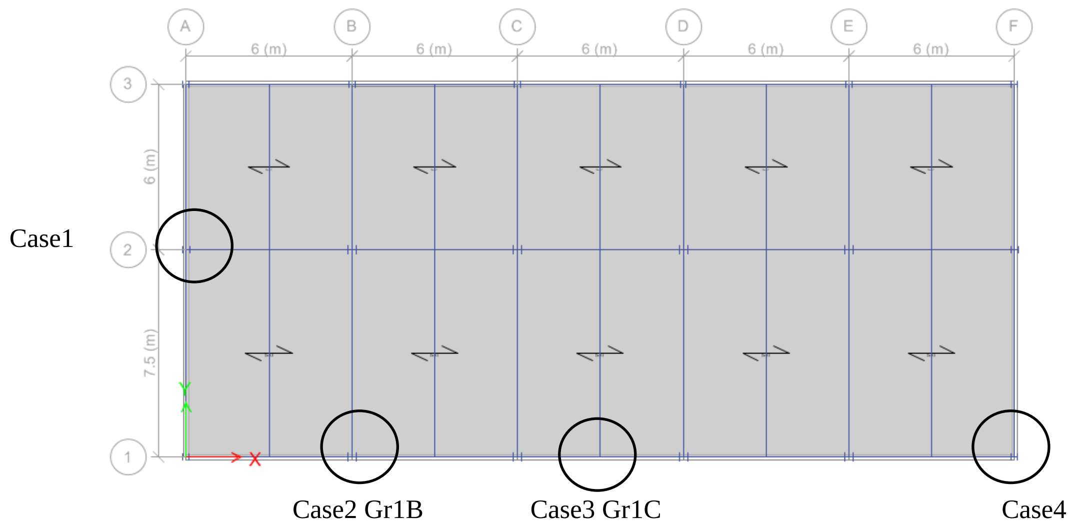

Figure 4.19: The locations of columns to be removed is based on the GSA guideline (IR4F).

4.4.1 PC Potential of IR4F Building with I-Beams, (IR4F-I)

Demand Capacity Ratio’s calculated for the Irregular Building, where the first 4 floors with I-beams between gridlines 1-2/C-D are removed. Figure 4.20 shows that none of the DCR’s of members are more than 2.0. Therefore, the potential of PC is not high.

However, this is not true for Case2 Gr1B, Case3 Gr1C and Case4. Figures 4.21 to 4.23 show that some of the members achieved DCR>2.0.   Hence the potential of PC is high.

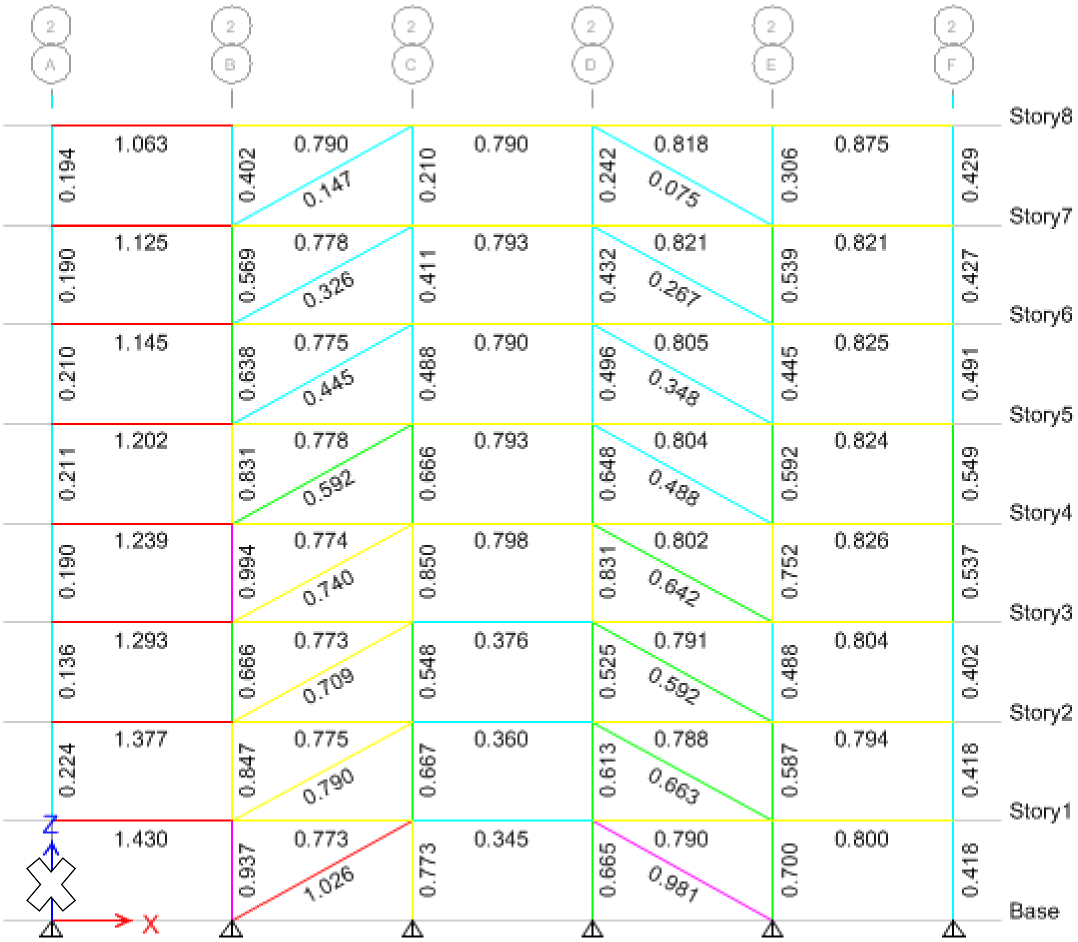

Figure 4.20: DCRs IR4F-I Case 1 - column is removed from the short side of the building.

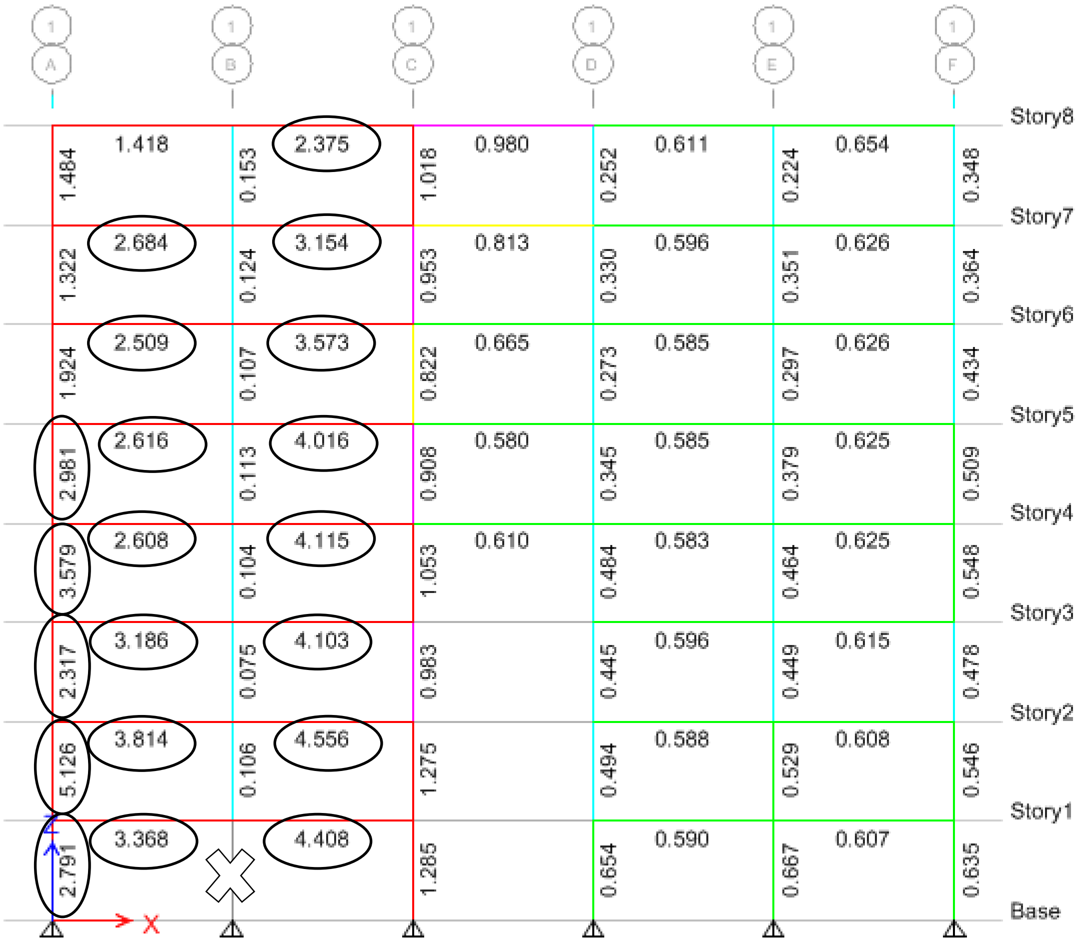

Figure 4.21: DCRs IR4F-I Case 2 - column is removed from the long side (Gr1B) of the building.

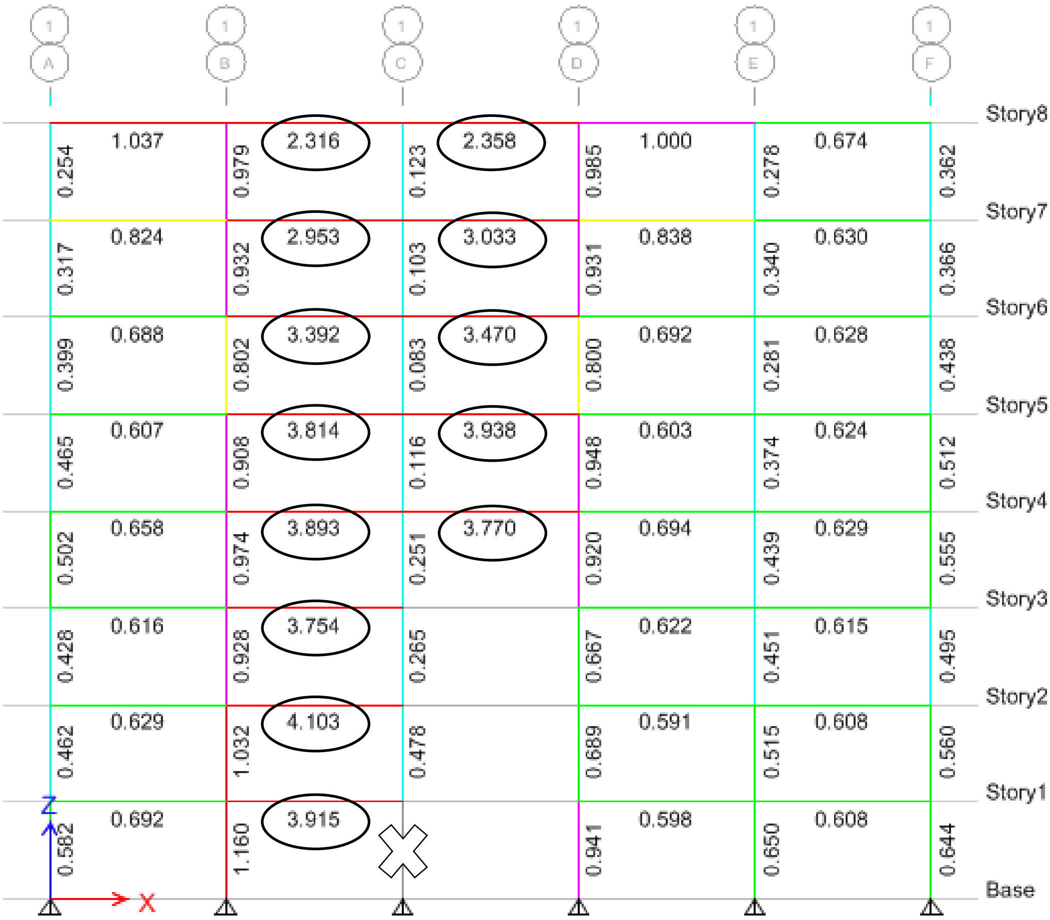

Figure 4.22: DCRs IR4F-I Case 3 - column is removed from the long side (Gr1C) of the building.

Figure 4.23: DCRs IR4F-I Case 4 - column is removed from the corner of the building.

4.4.2 PC Potential of IR4F Building with Truss Beams, (IR4F-T)

PC potential of Case1 is not high since no member DCR is more than 2.0 (Figure 4.24). On the other hand for Case2 Gr1B, Case3 Gr1C and Case4 the risk of PC is high since some members achieved DCR values more than the accepted limits (Figures 4.25 to 4.27). This has been the trend for all the other cases presented in earlier sections.

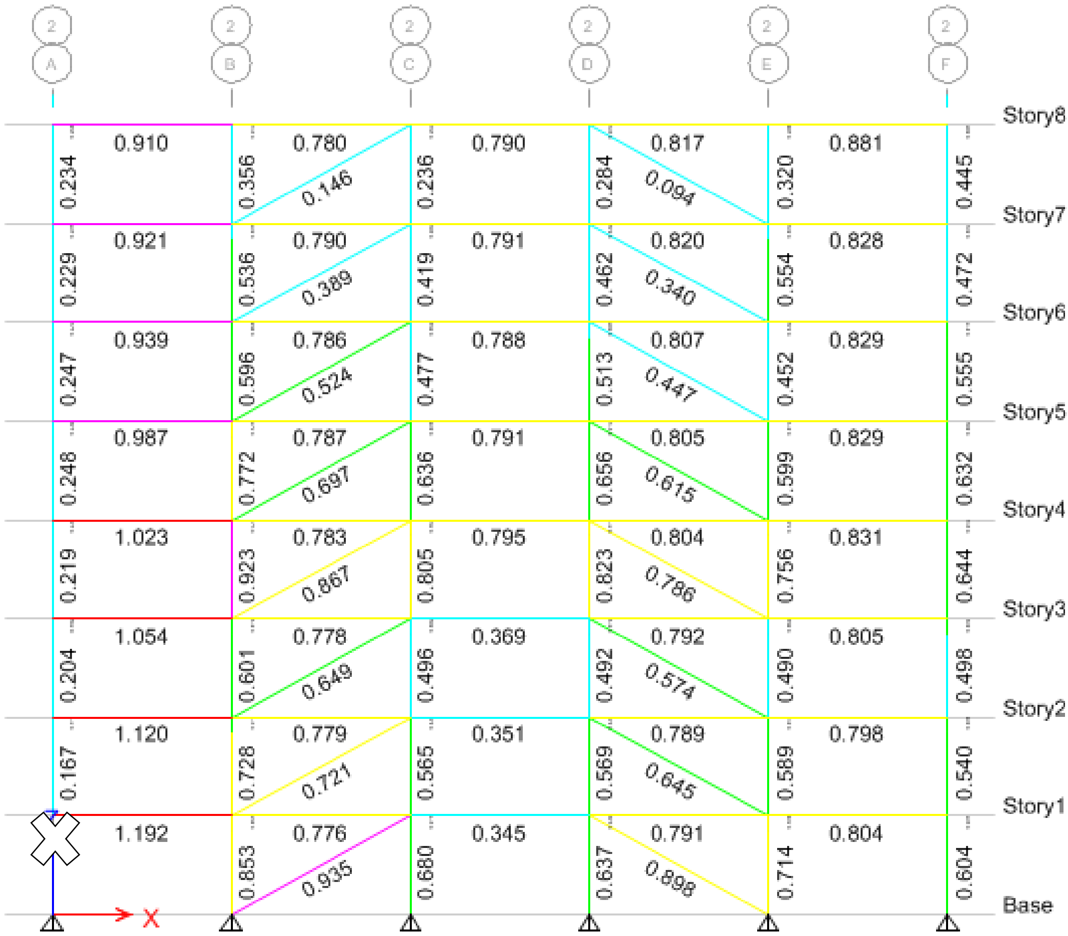

Figure 4.24: DCRs IR4F-T Case 1 - column is removed from the short side of the building.

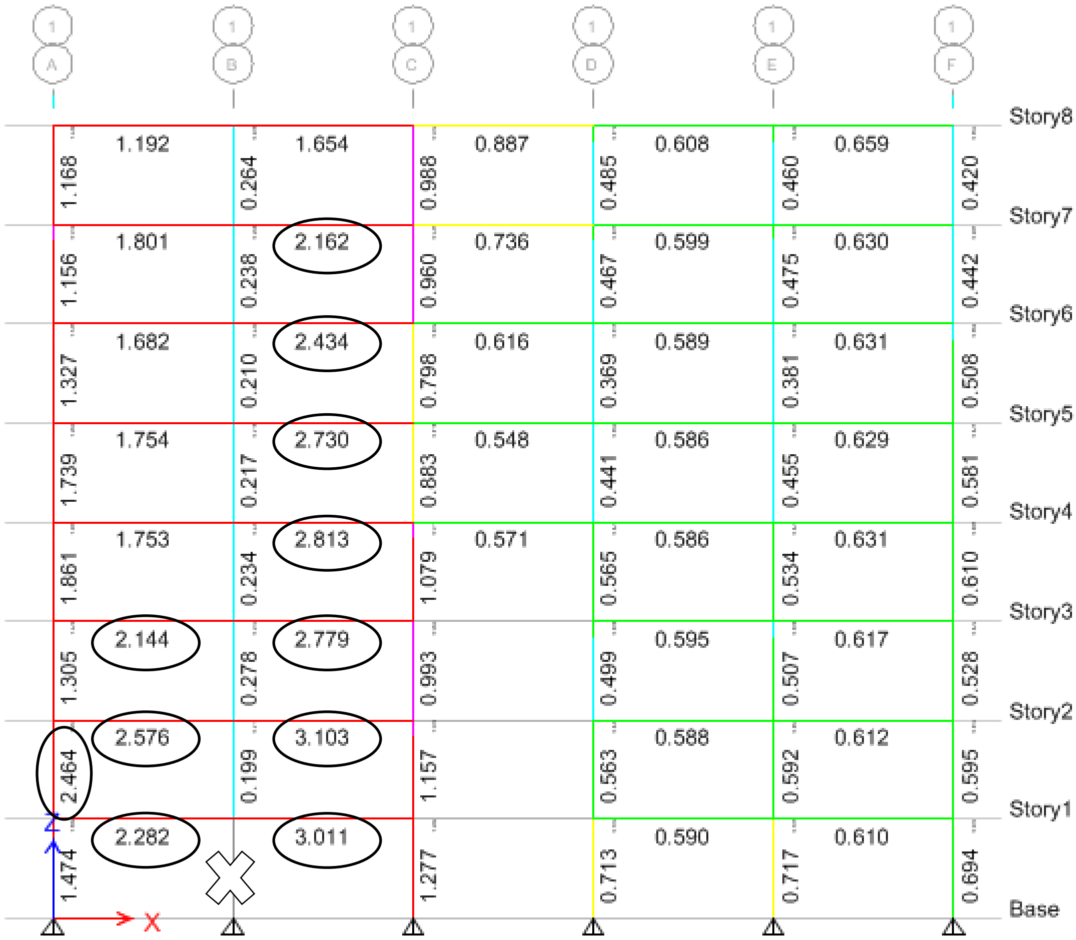

Figure 4.25: DCRs IR4F-T Case 2 - column is removed from the long side (Gr1B) of the building.

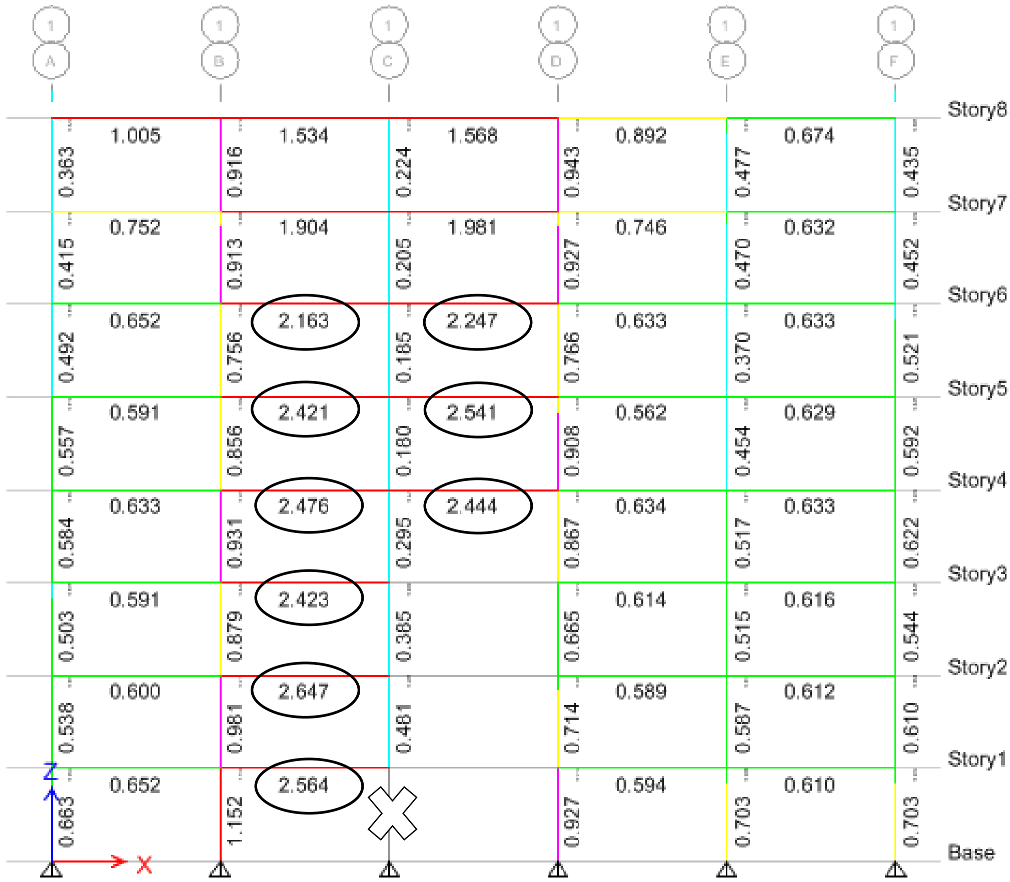

Figure 4.26: DCRs IR4F-T Case 3 - column is removed from the long side (Gr1C) of the building.

Figure 4.27: DCRs IR4F-T Case 4 - column is removed from the corner of the building.

4.5 Rehabilitation of Regular Buildings, (RB)

According to the analysis results, the failed beams and columns were located and then the rehabilitation plans was applied. The rehabilitation is carried out by replacing the column removed with a system of bracing members to resist the loads that caused the failure. Due to the behaviour mechanism of the bracings, the relocated bracings will transfer the loads coming from the upper beams to the lower column in the neighbouring bay. The connection type which is used in this situation is very crucial, both for the load transfer mechanism and for the column section behaviour.

4.5.1 Rehabilitation of Regular Building with I-Beams, (RB-I)

The failed beams are located and rehabilitation plan was applied for Cases 2,3 and 4.

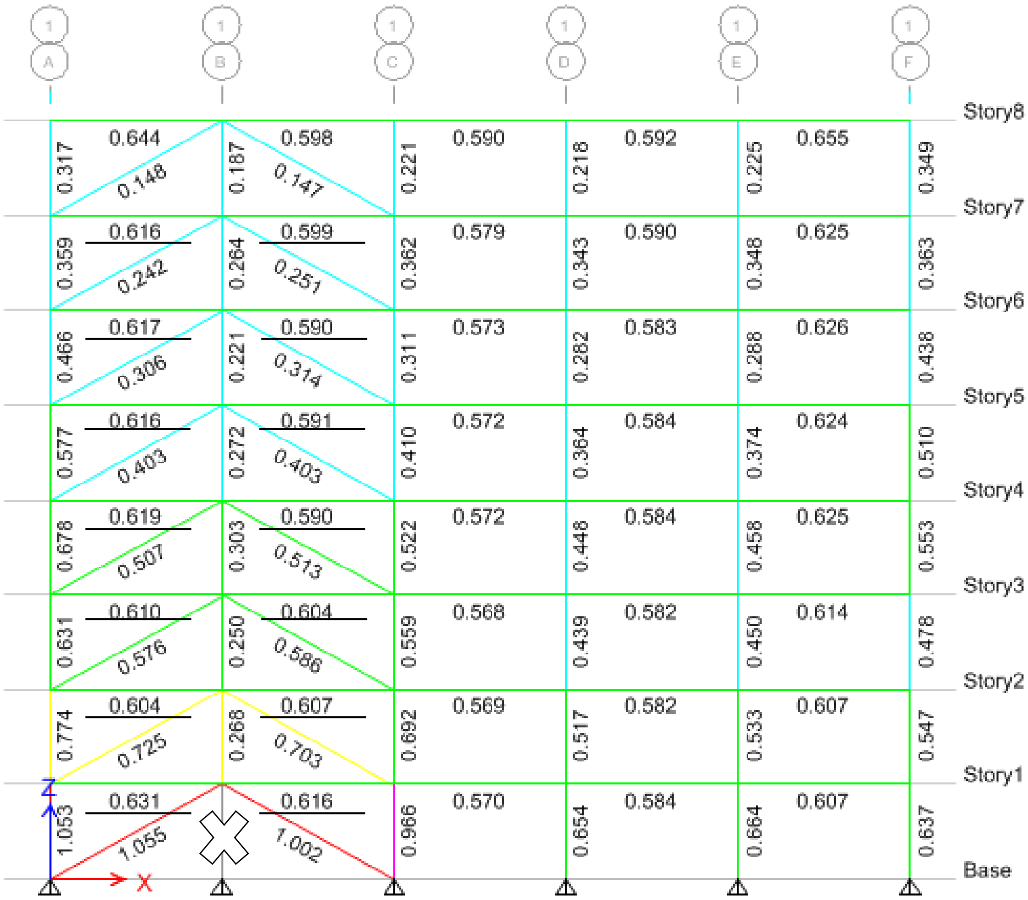

Figure 4.28: DCRs after rehabilitating RB-I Case 2 - column is removed from the long side (Gr1B) of the building.

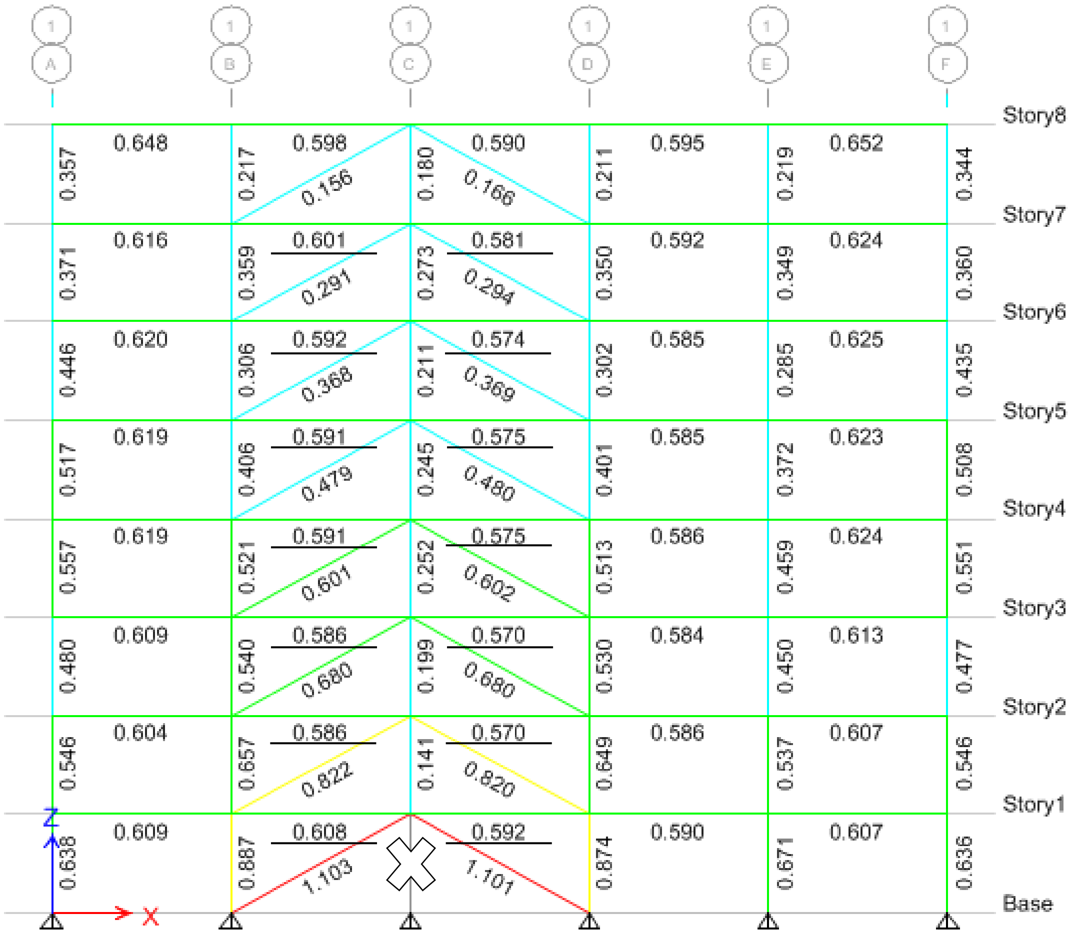

Figure 4.29: DCRs after rehabilitating RB-I Case 3 - column is removed from the long side (Gr1C) of the building.

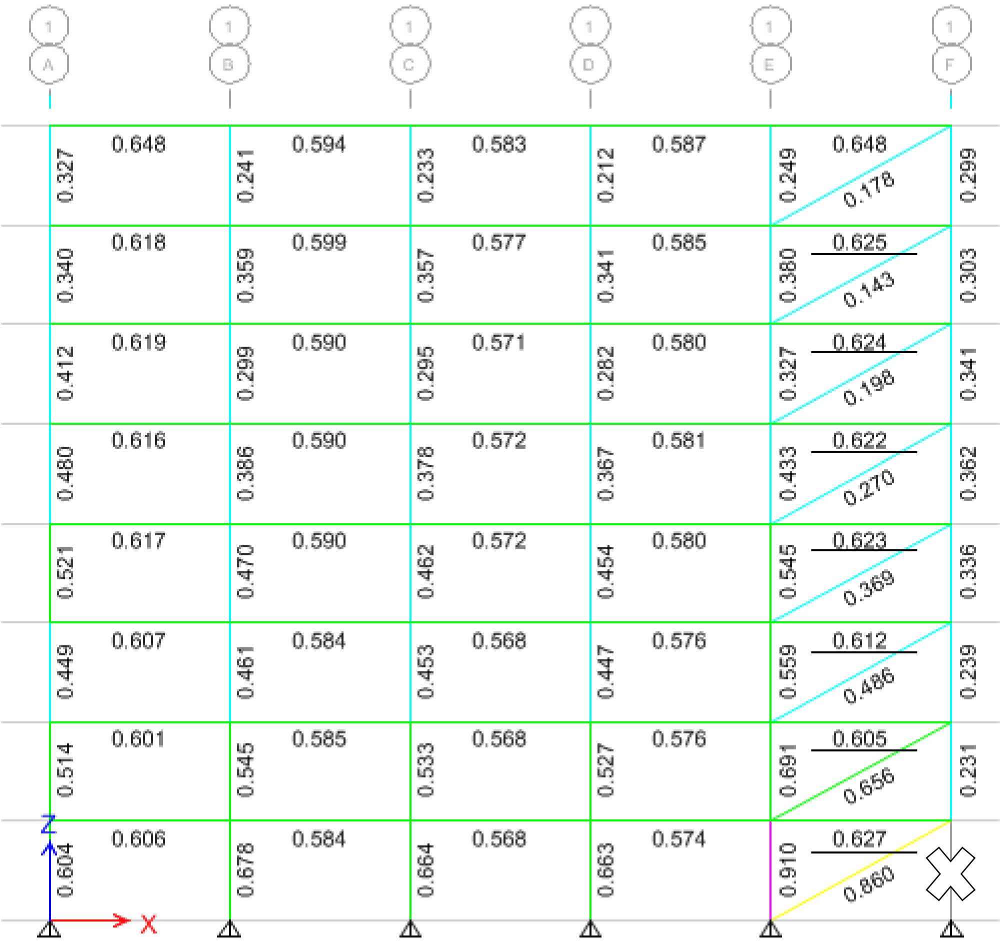

Figure 4.30: DCRs after rehabilitating RB-I Case 4 - column is removed from the corner of the building.

4.5.2 Rehabilitation of Regular Building with Truss Beams, (RB-T)

The failed beams are located and rehabilitation plan was applied for Cases 2,3 and 4.

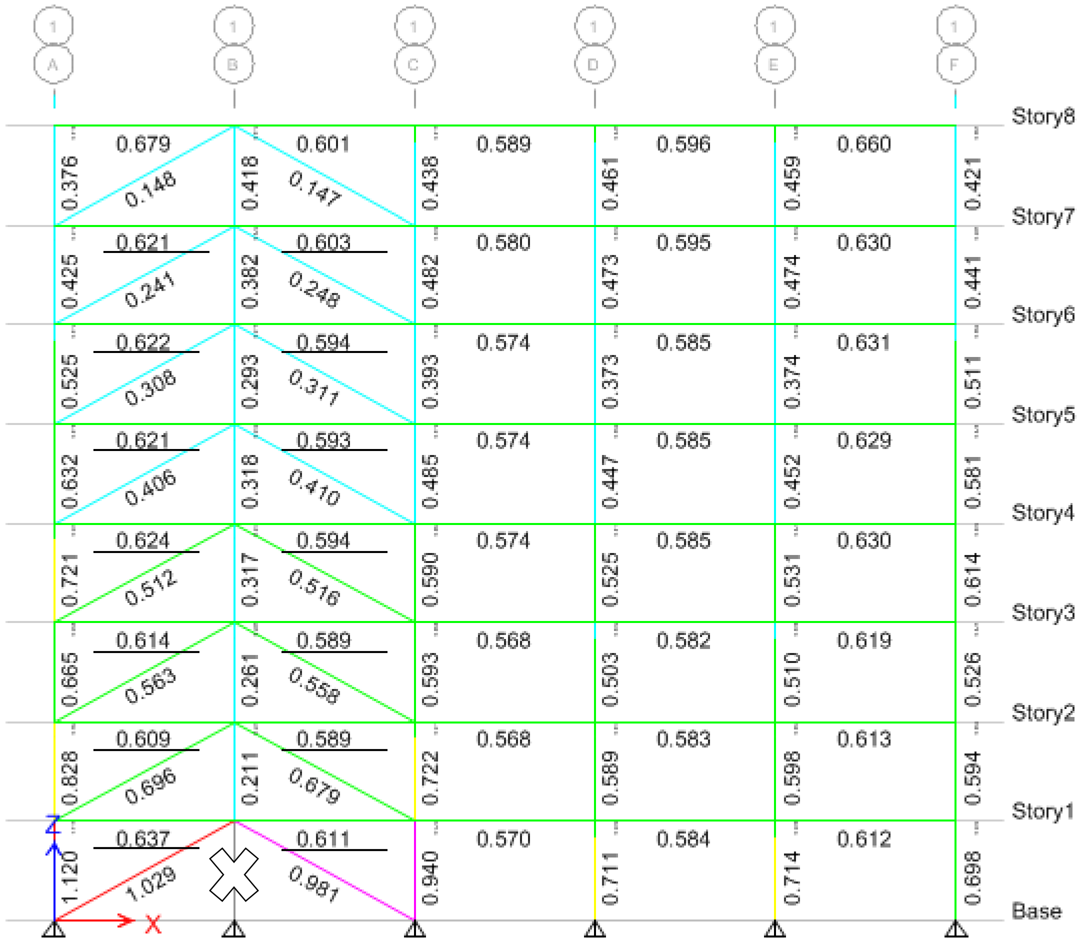

Figure 4.31: DCRs after rehabilitating RB-T Case 2 - column is removed from the long side (Gr1B) of the building.

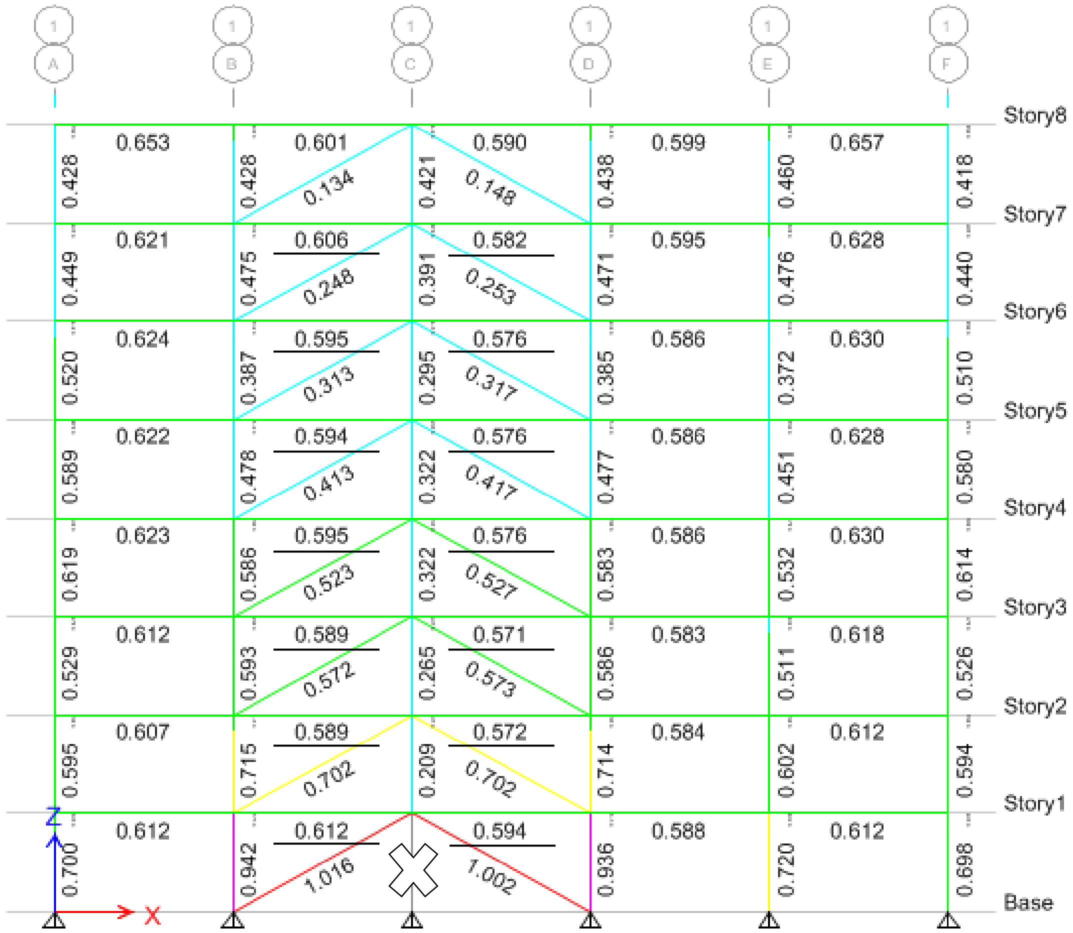

Figure 4.32: DCRs after rehabilitating RB-T Case 3 - column is removed from the long side (Gr1C) of the building.

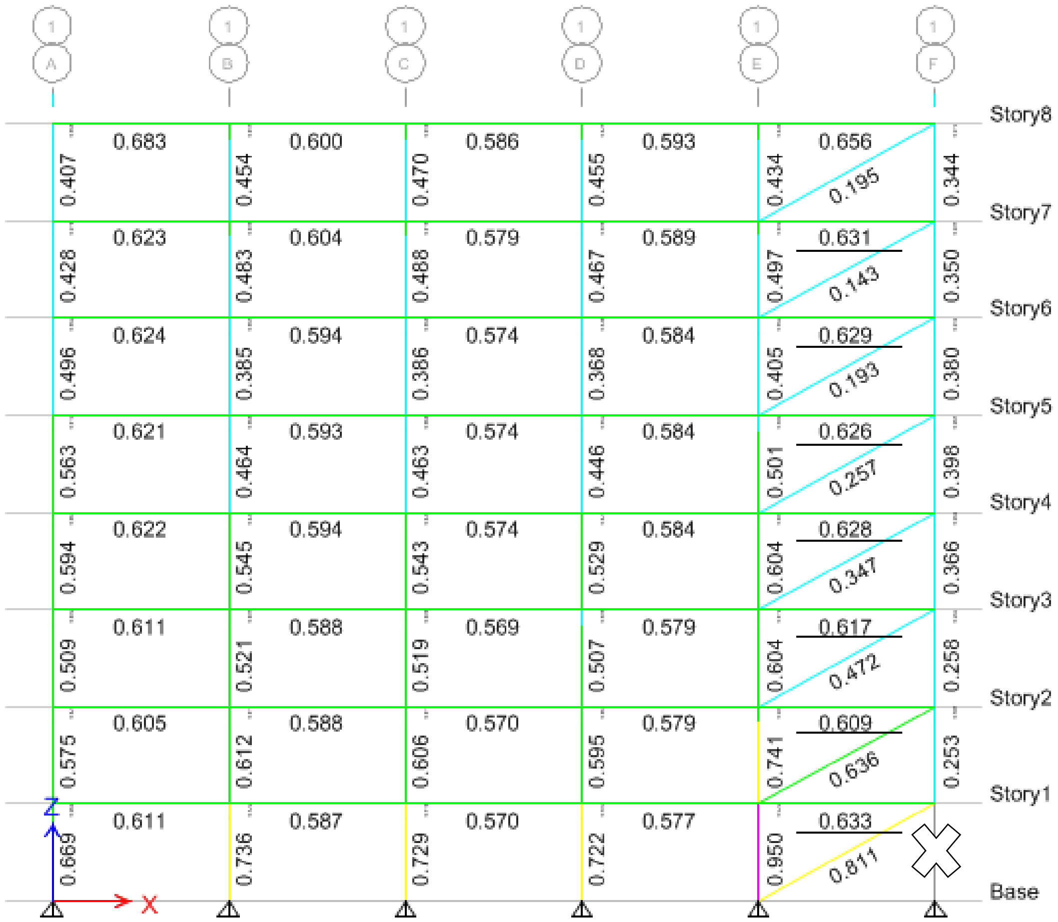

Figure 4.33: DCRs after rehabilitating RB-T Case 4 - column is removed from the corner of the building.

4.6 Rehabilitation of Irregular Buildings, (IR8F)

The failed beams and columns were located and the rehabilitation plan was applied. The column removed was replaced by a system of bracing members to resist the failure loads. The relocated bracings were transferring the loads coming from the upper beams to the lower column in the neighbouring bay.

4.6.1 Rehabilitation of IR8F Building with I-Beams, (IR8F-I)

The failed beams are located and rehabilitation plan was applied for Cases 2,3 and 4.

Figure 4.34: DCRs after rehabilitating IR8F-I Case 2 – column is removed from the long side (Gr1B) of the building.

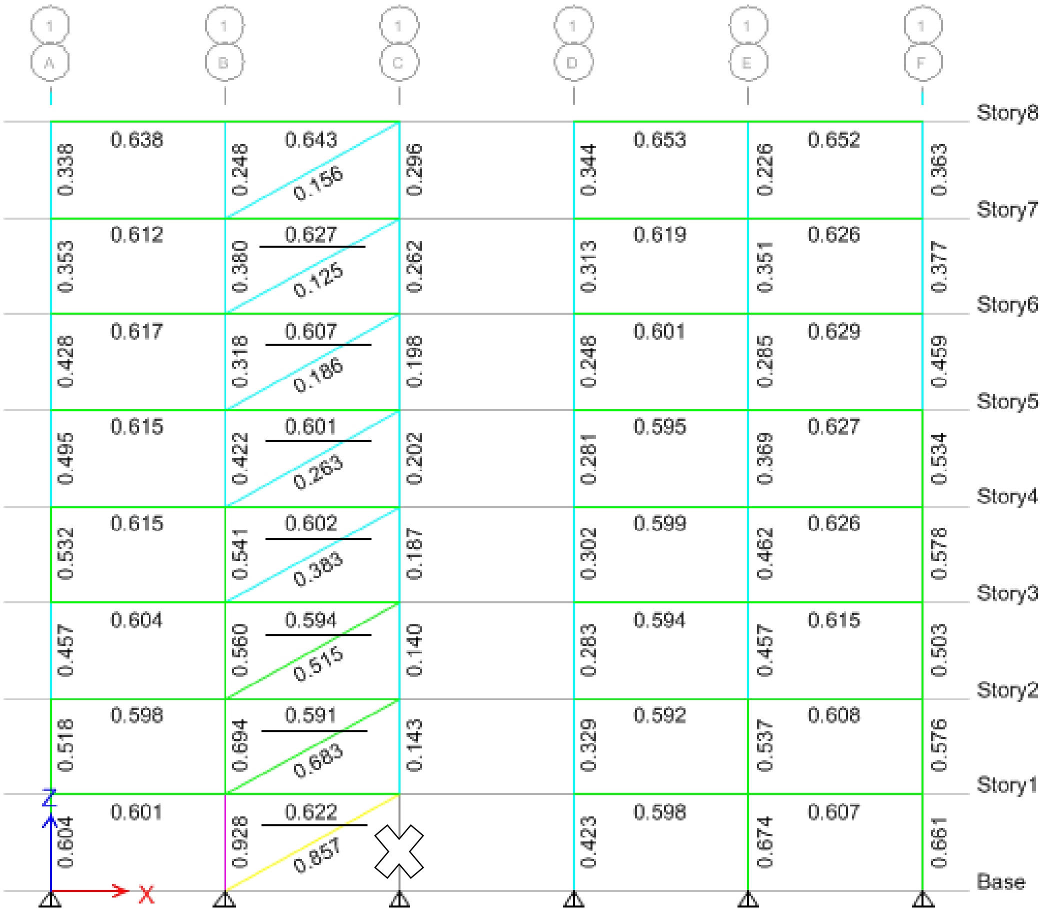

Figure 4.35: DCRs after rehabilitating IR8F-I Case 3 – column is removed from the long side (Gr1C) of the building.

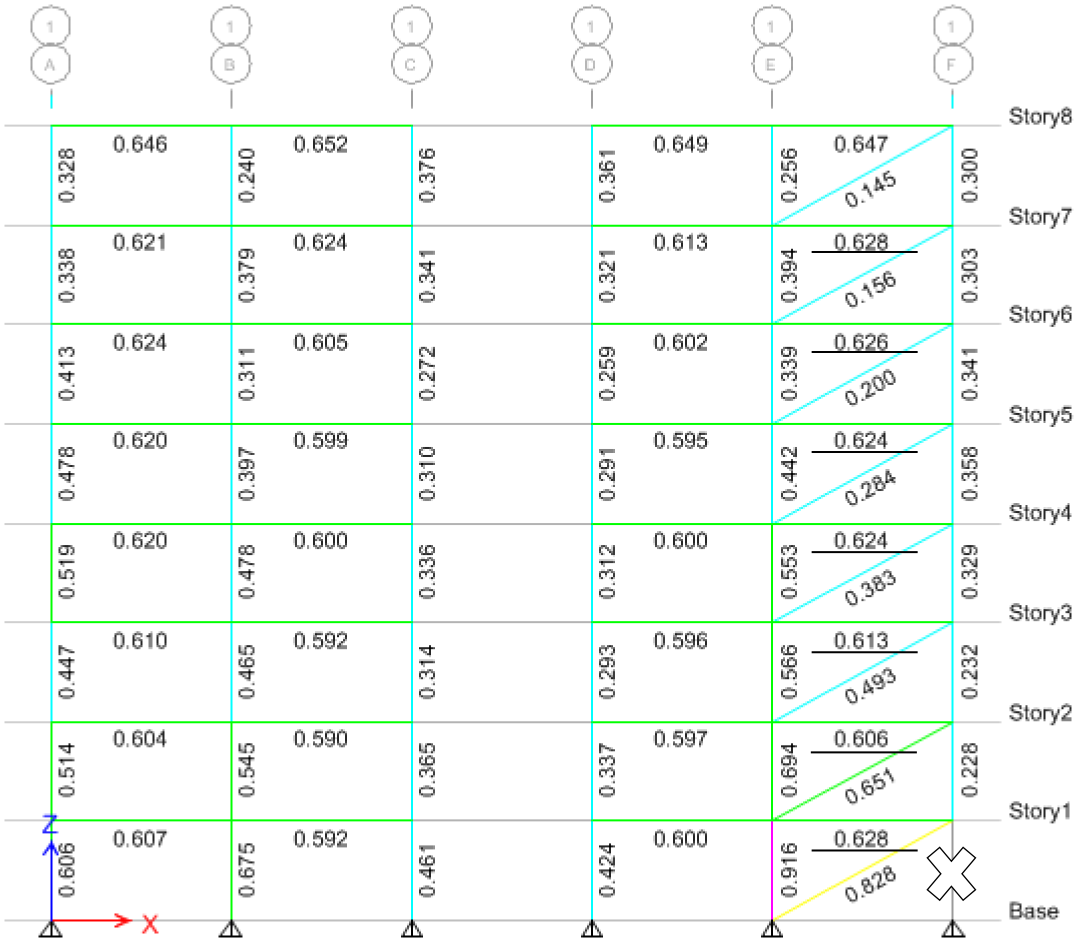

Figure 4.36: DCRs after rehabilitating IR8F-I Case 4 – column is removed from the side corner of the building.

4.6.2 Rehabilitation of IR8F Building with Truss Beams, (IR8F-T)

The failed beams are located and rehabilitation plan was applied for Cases 2,3 and 4.

Figure 4.37: DCRs after rehabilitating IR8F-T Case 2 – column is removed from the long side (Gr1B) of the building.

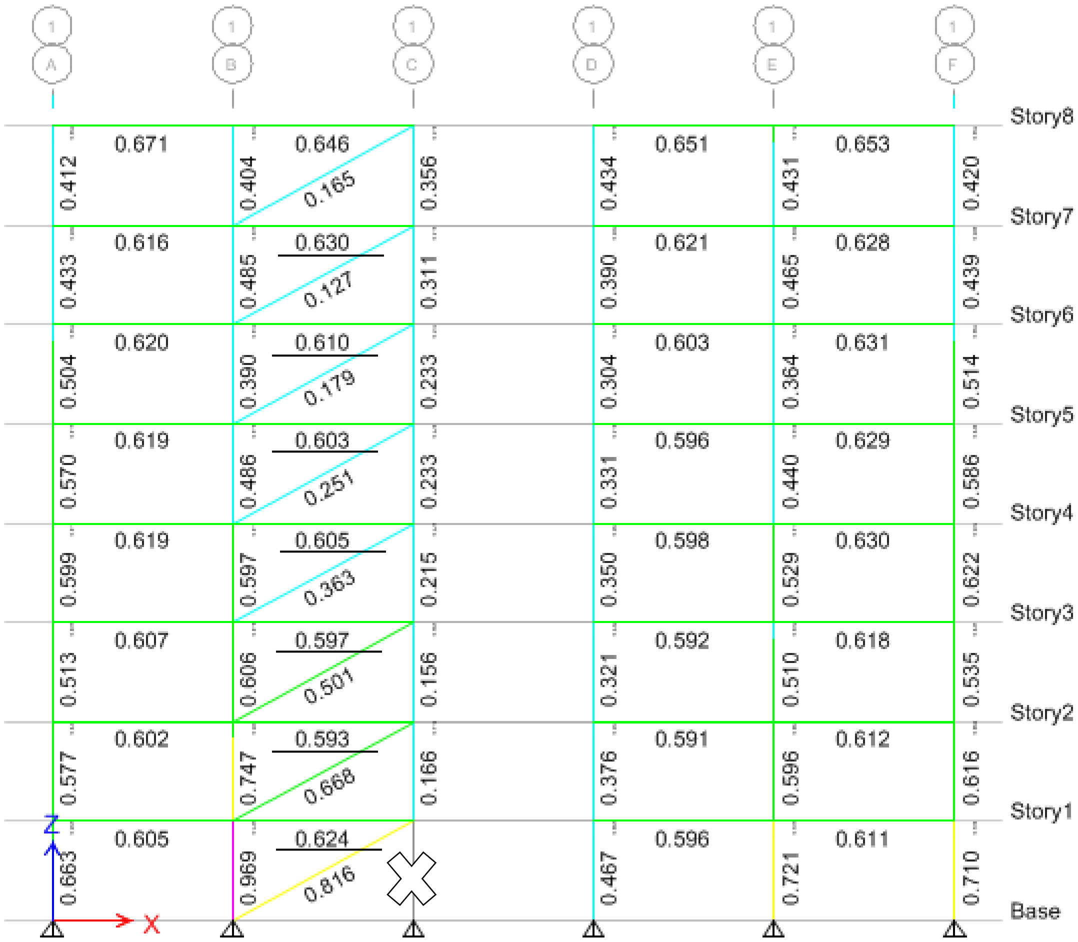

Figure 4.38: DCRs after rehabilitating IR8F-T Case 3 – column is removed from the long side (Gr1C) of the building.

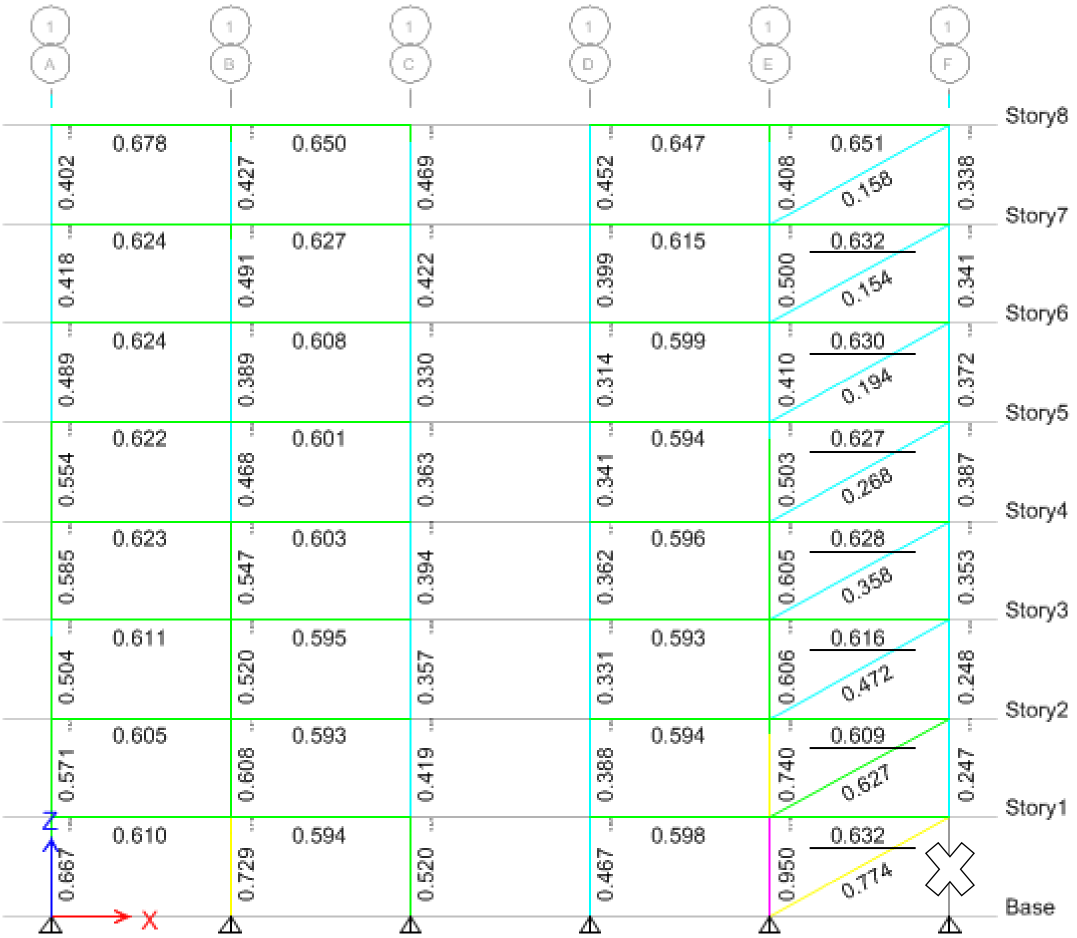

Figure 4.39: DCRs after rehabilitating IR8F-T Case 4 – column is removed from the corner of the building.

4.7 Rehabilitation of Irregular Buildings, (IR4F)

The failed beams are located. Then, rehabilitation plans have been applied. The rehabilitation depends on replacing the removed column with a system of bracing members to resist the failure. Due to the mechanism behaviour of the bracing, the relocated bracings will transfer the loads coming from the upper beams to the lower column in the neighbouring bay.

4.7.1 Rehabilitation of IR4F Building with I-Beams, (IR4F-I)

The failed beams of IR4F-I are located and rehabilitation plan was applied for Cases 2, 3 and 4.

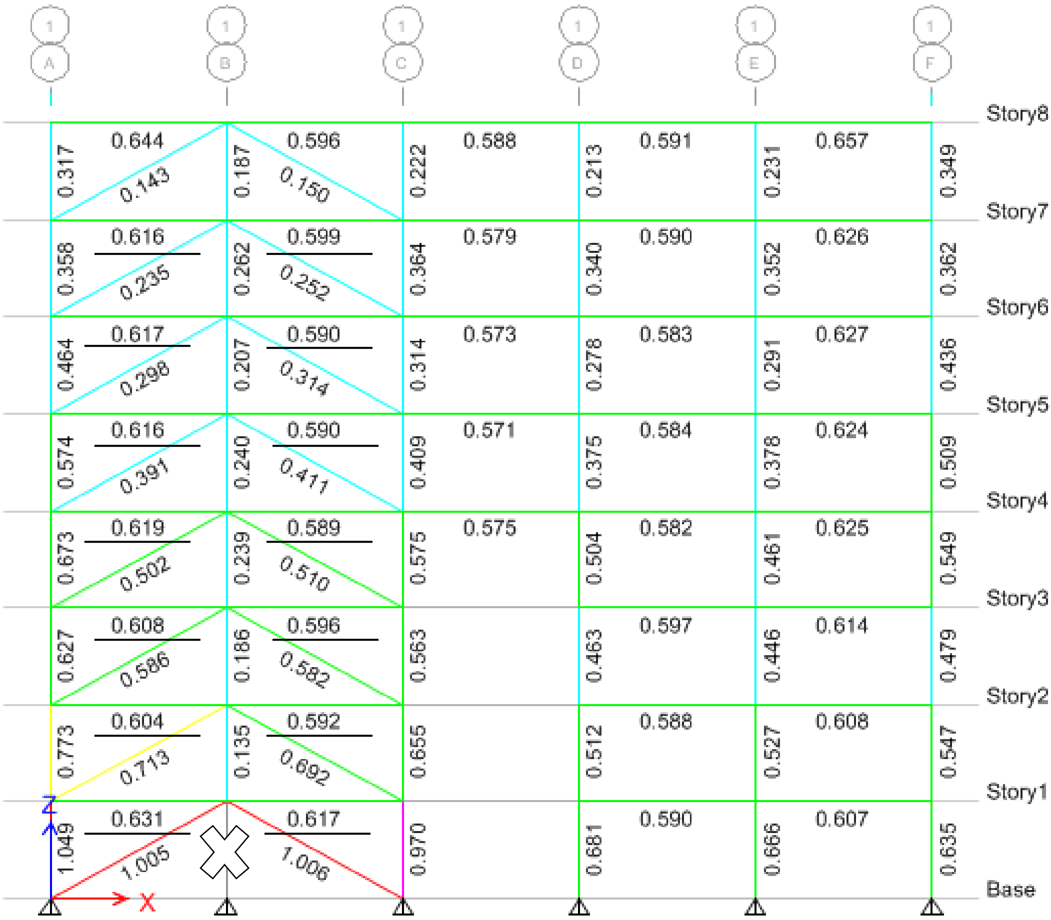

Figure 4.40: DCRs after rehabilitating IR4F-I Case 2 – column is removed from the long side (Gr1B) of the building.

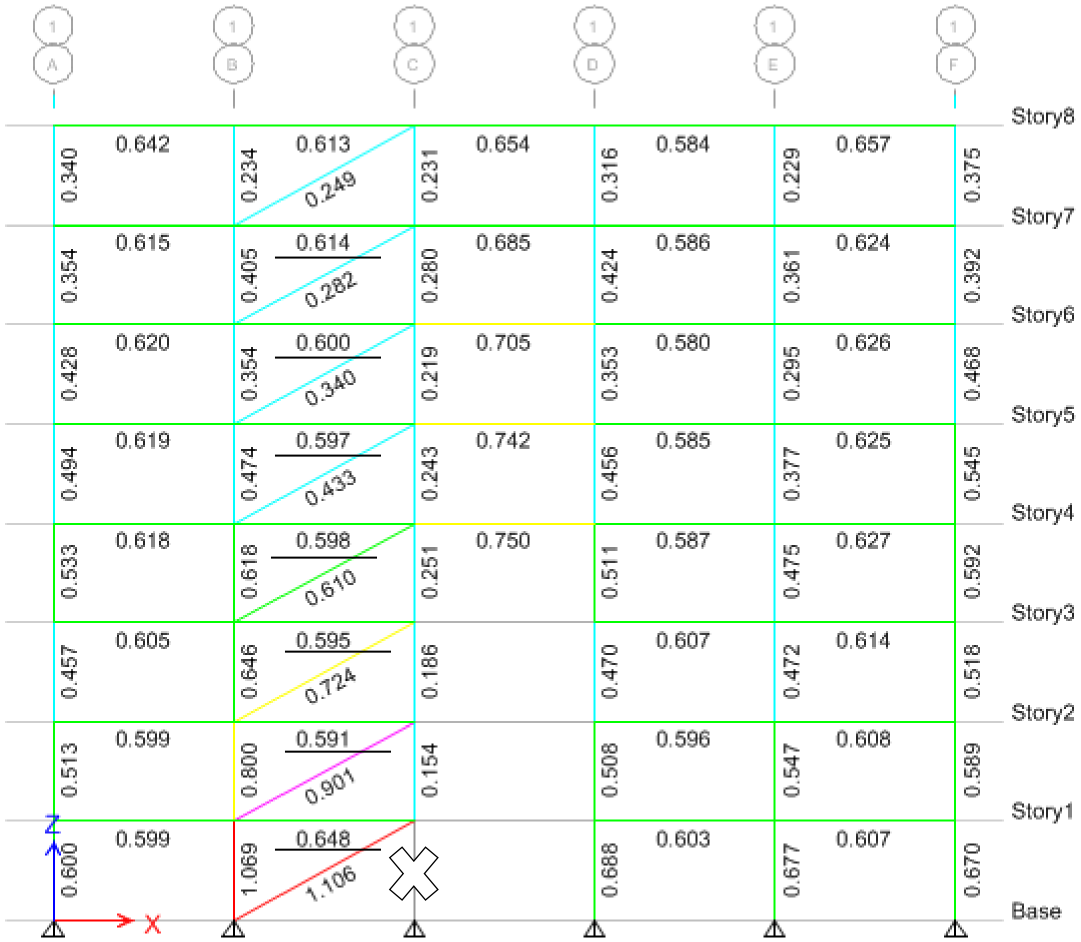

Figure 4.41: DCRs after rehabilitating IR4F-I Case 3 – column is removed from the long side (Gr1C) of the building.

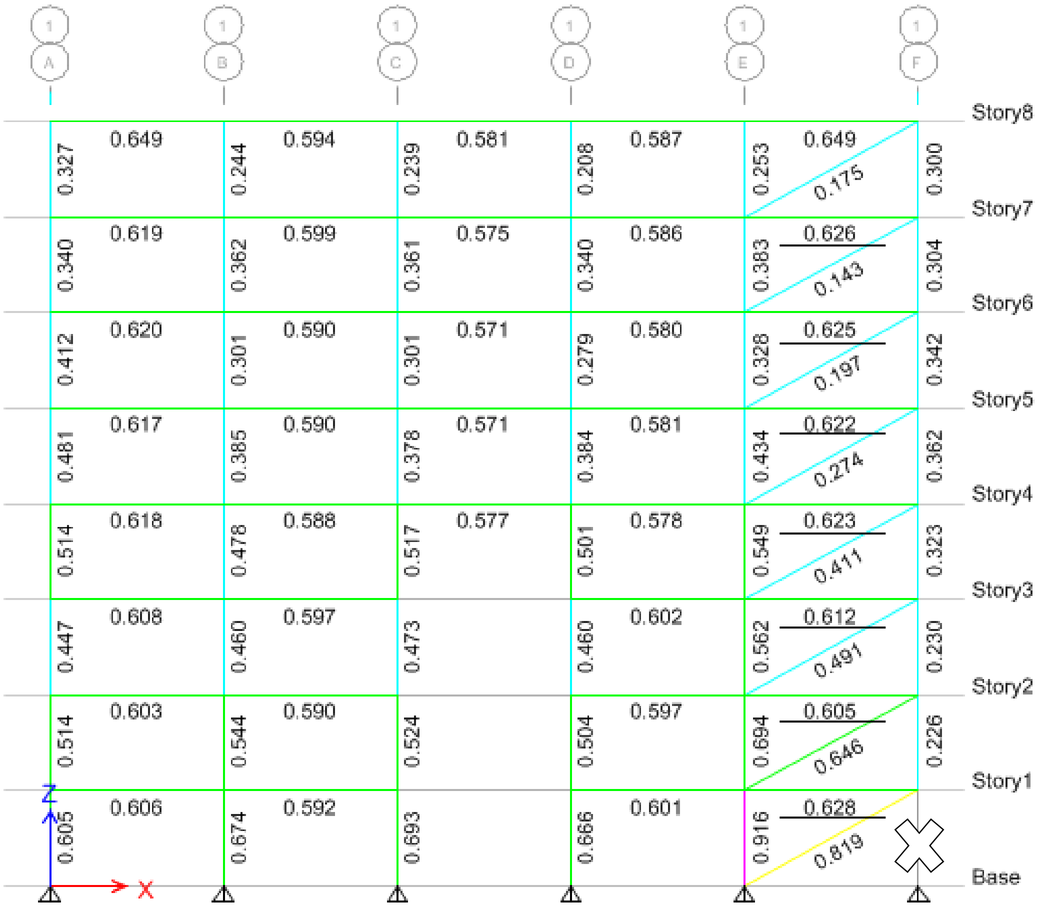

Figure 4.42: DCRs after rehabilitating IR4F-I Case 4 – column is removed from the corner of the building.

4.7.2 Rehabilitation of IR4F Building with Truss Beams, (IR4F-T)

The failed beams are located for IR4F-T and rehabilitation plan was applied for Cases 2,3 and 4.

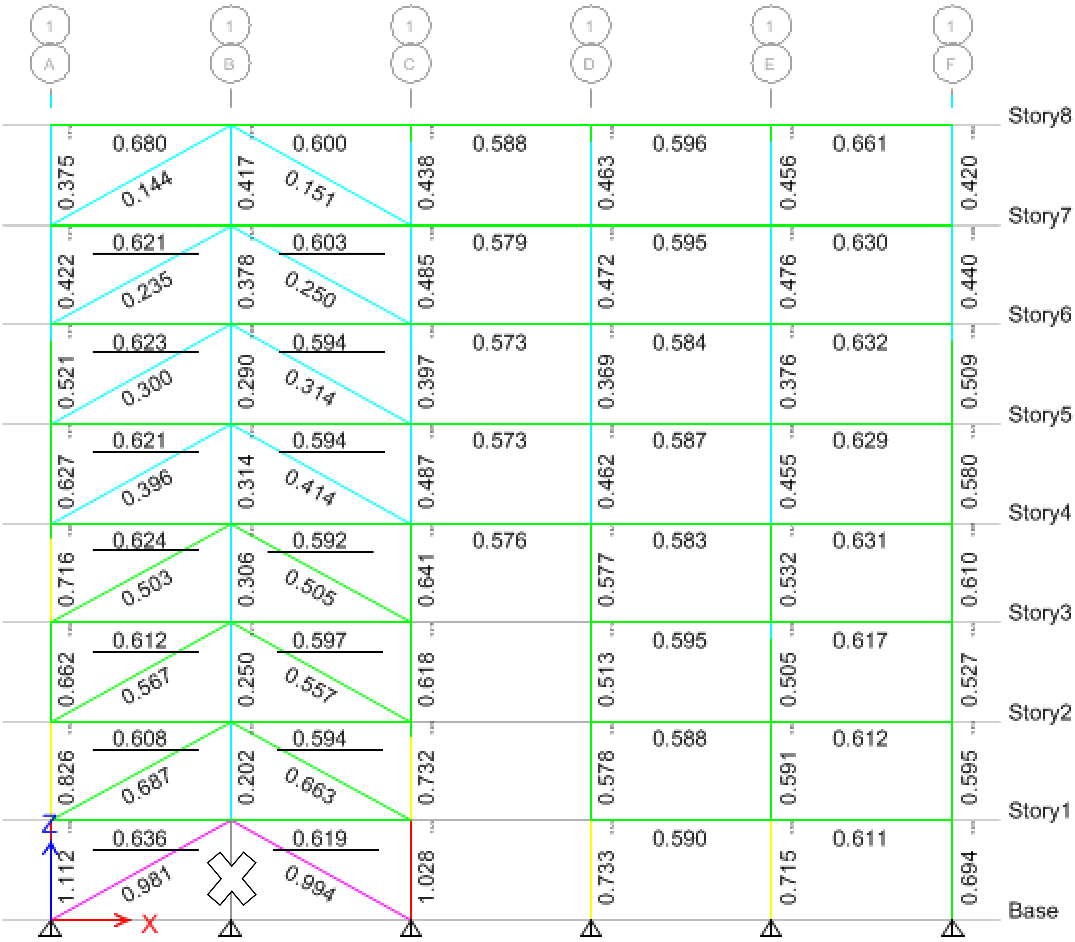

Figure 4.43: DCRs after rehabilitating IR4F-T Case 2 – column is removed from the long side (Gr1B) of the building.

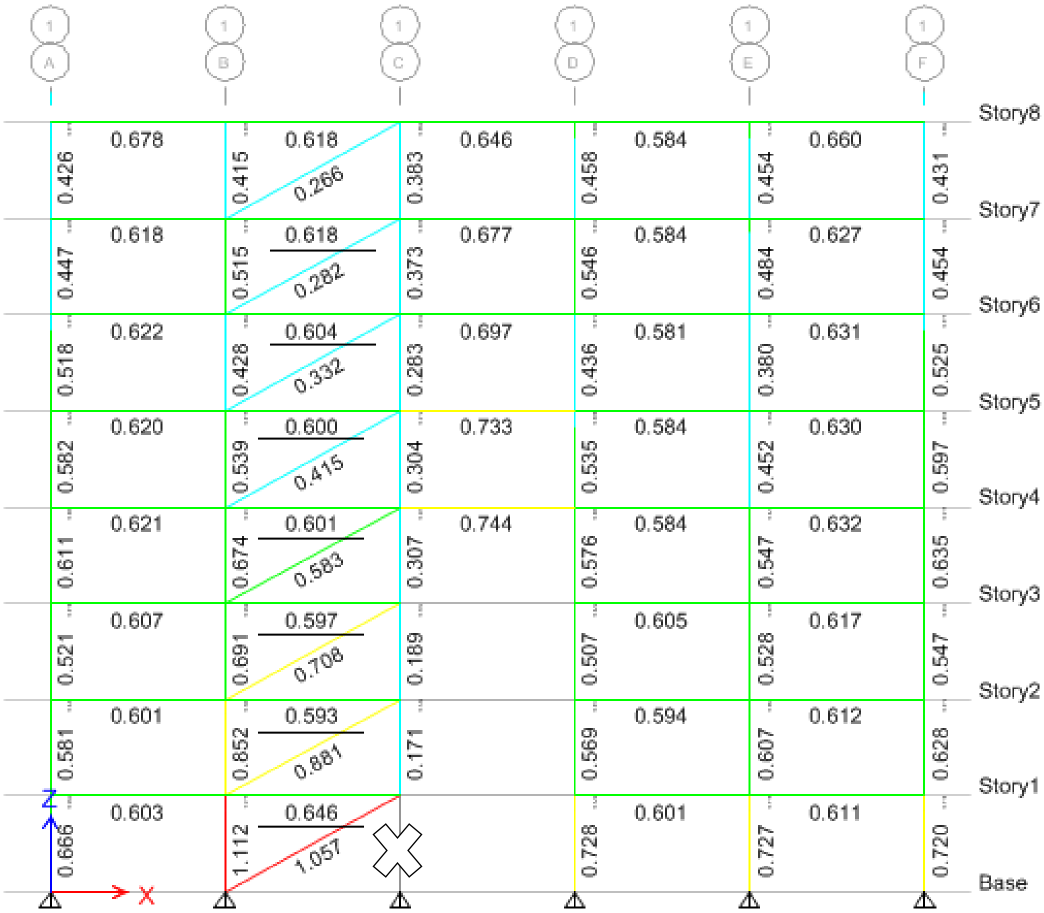

Figure 4.44: DCRs after rehabilitating IR4F-T Case 3 – column is removed from the long side (Gr1C) of the building.

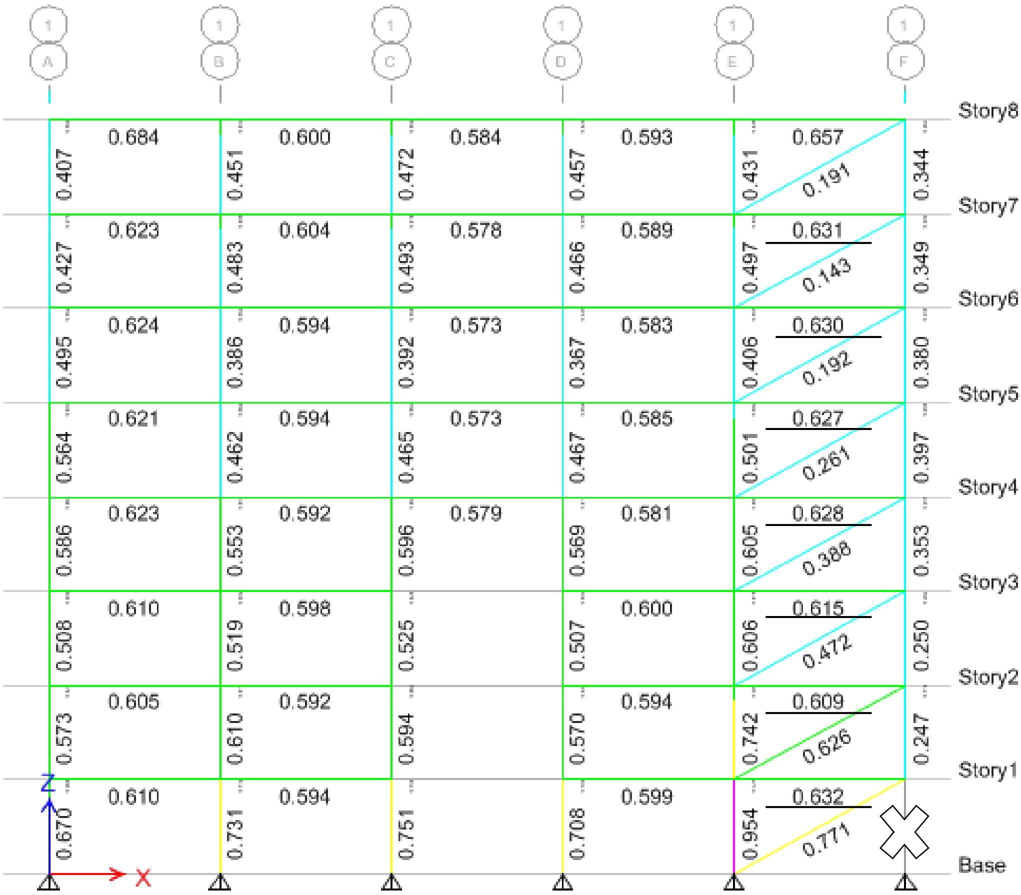

Figure 4.45: DCRs after rehabilitating IR4F-T Case 4 – column is removed from the corner of the building.

When columns were removed from short and long sides and corner of the building the magnitude of DCRs were higher for floors with I-beams when compared with floors with truss beams.

Chapter 5

RESULTS AND DISCUSSIONS FOR NONLINEAR STATIC (PUSHOVER) ANALYSIS

5.1 Introduction

In this chapter, result of the analysis and the acceptance criteria for PC pushover analysis of beams and columns are presented.

5.2 Definition of Moment, Plastic Rotation and Hinge Status

The plastic rotation is the inelastic rotation or nonrecoverable rotation that occurs after the yield rotation is reached. In addition, it entire cross section has yielded. The plastic rotation is typically associated with a discrete plastic hinge that is inserted into a numerical frame model. The plastic hinge measures both elastic and plastic rotations, although for simplicity, the elastic portion is often ignored due to its small size. For steel the nonlinear acceptance criteria and the modeling parameters in terms of plastic rotation. Figure 5.1 shows definition of yield rotation, plastic rotation and total rotation.

In addition, there are several performance level such as, AI, IO, LS and CP. Results of the performance level for PC pushover analysis of beams and columns are presented for all building types.

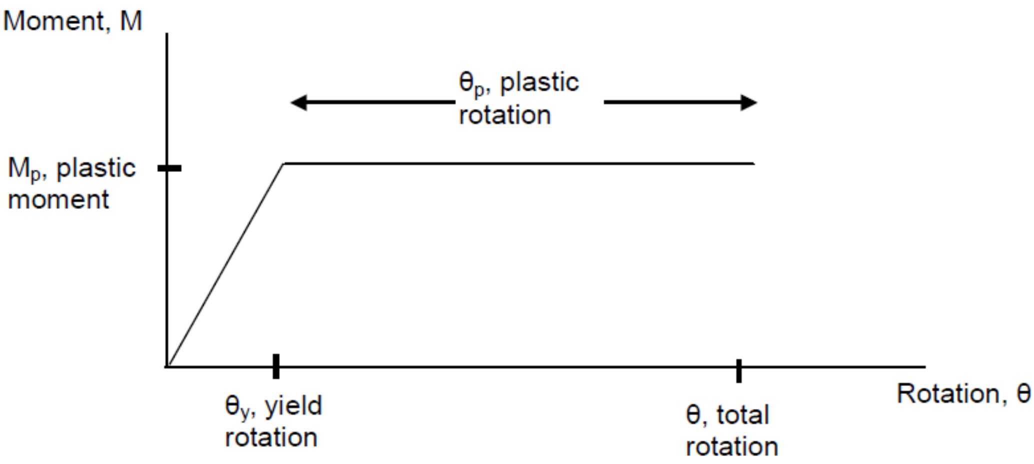

Figure 5.1: Definition of yield rotation, plastic rotation and total rotation.

5.3 Regular Buildings, (RB)

Column removal locations as Case1, Case2, Case3 and Case4 are illustrated in Chapter 4, Figure 4.1, The rotation values obtained as a result of pushover analysis for the trusses are less than the rotation values of the I-beams for all RB. On the other hand, the rotation values for all the RB-I and RB-T columns are less than the values given by acceptance criteria. Therefore, the building with truss beams has lower potential for PC when a column is suddenly removed.

5.3.1 PC Potential of Regular Building with I-Beams Due to Pushover Analysis, (RB-I)

Rotation's calculated for Regular Building, then compared for each case of the structure with I-beams in this section. Table 5.1 shows that none of the element rotations are more than 0.21. Tables 5.2 to 5.4 indicates that some of the members achieved rotations more than the accepted limits.

Table 5.1: Beam rotations for RB-I Case 1 - column removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	496.42	0.0828	>CP
Story8	B11	Push Y Min	-485.4	-0.1274	>CP
Story6	B11	Push Y Max	488.16	0.126	>CP
Story6	B11	Push Y Min	-493.88	-0.132	>CP

Table 5.2: Beam rotations for RB-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 8,7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	396.65	0.2381	>CP	B11	Push Y Max	404.12	0.2669	>CP	B11	Push Y Max	406.61	0.2636	>CP
B11	Push Y Min	-409.6	-0.286	>CP	B11	Push Y Min	-413.53	-0.2767	>CP	B11	Push Y Min	-412.08	-0.2707	>CP
B15	Push Y Max	396.03	0.2337	>CP	B15	Push Y Max	404.30	0.2673	>CP	B15	Push Y Max	407.37	0.2637	>CP
B15	Push Y Min	-407.83	-0.2937	>CP	B15	Push Y Min	-410.68	-0.2784	>CP	B15	Push Y Min	-413.73	-0.2706	>CP
B15	Push Y Max	409.18	0.2697	>CP	B16	Push Y Max	270.73	0.4822	>CP	B16	Push Y Max	267.11	0.4837	>CP
B15	Push Y Min	-412.29	-0.2835	>CP	B16	Push Y Min	-266.59	-0.4839	>CP	B16	Push Y Min	-263.55	-0.4839	>CP
B16	Push Y Max	271.08	0.4822	>CP	B17	Push Y Max	272.12	0.4834	>CP	B17	Push Y Max	269.87	0.4839	>CP
B16	Push Y Min	-266.71	-0.4827	>CP	B17	Push Y Min	-267.62	-0.4827	>CP	B17	Push Y Min	-266.72	-0.4836	>CP
B16	Push Y Max	270.39	0.4824	>CP	B19	Push Y Max	272.20	0.4834	>CP	B19	Push Y Max	269.82	0.4836	>CP
B16	Push Y Min	-260.40	-0.4817	>CP	B19	Push Y Min	-267.70	-0.4827	>CP	B19	Push Y Min	-266.67	-0.4834	>CP
B17	Push Y Max	272.31	0.4838	>CP	B20	Push Y Max	270.72	0.4823	>CP	B20	Push Y Max	267.22	0.482	>CP
B17	Push Y Min	-263.55	-0.4821	>CP	B20	Push Y Min	-266.53	-0.4842	>CP	B20	Push Y Min	-263.71	-0.4842	>CP
B17	Push Y Max	272.95	0.4842	>CP										
B17	Push Y Min	-270.41	-0.4826	>CP										
B19	Push Y Max	272.82	0.4833	>CP										
B19	Push Y Min	-270.28	-0.4819	>CP										
B19	Push Y Max	272.03	0.4816	>CP										
B19	Push Y Min	-265.74	-0.4811	>CP										
B20	Push Y Max	270.93	0.4832	>CP										
B20	Push Y Min	-261.17	-0.4842	>CP										

Table 5.2: (continued) Beam rotations for RB-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 5,4, 3 and 2).

Story 5

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	404.17	0.2446	>CP
B11	Push Y Min	-411.08	-0.254	>CP
B15	Push Y Max	404.61	0.2446	>CP
B15	Push Y Min	-411.72	-0.2541	>CP
B16	Push Y Max	264.26	0.4828	>CP
B16	Push Y Min	-262.26	-0.4830	>CP
B17	Push Y Max	264.31	0.4832	>CP
B17	Push Y Min	-260.61	-0.4841	>CP
B19	Push Y Max	265.17	0.4833	>CP
B19	Push Y Min	-260.98	-0.4842	>CP
B20	Push Y Max	266.72	0.4827	>CP
B20	Push Y Min	-262.81	-0.4828	>CP

Story 4

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	402.60	0.206	>CP
B11	Push Y Min	-407.19	-0.2107	>CP
B15	Push Y Max	402.82	0.206	>CP
B15	Push Y Min	-407.51	-0.2107	>CP
B16	Push Y Max	259.66	0.4338	>CP
B16	Push Y Min	-258.94	-0.4329	>CP
B17	Push Y Max	257.29	0.3648	>CP
B17	Push Y Min	-256.30	-0.366	>CP
B19	Push Y Max	257.99	0.3652	>CP
B19	Push Y Min	-256.77	-0.3663	>CP
B20	Push Y Max	261.97	0.4332	>CP
B20	Push Y Min	-259.33	-0.4323	>CP

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	255.82	0.3309	>CP
B16	Push Y Min	-254.11	-0.3306	>CP
B17	Push Y Max	252.25	0.2717	>CP
B17	Push Y Min	-251.46	-0.2726	>CP
B19	Push Y Max	250.03	0.2726	>CP
B19	Push Y Min	-251.1	-0.2733	>CP
B20	Push Y Max	255.16	0.3299	>CP
B20	Push Y Min	-253.41	-0.3297	>CP

Story 2

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	255.82	0.3309	>CP
B16	Push Y Min	-254.11	-0.3306	>CP
B17	Push Y Max	252.25	0.2717	>CP
B17	Push Y Min	-251.46	-0.2726	>CP
B19	Push Y Max	250.03	0.2726	>CP
B19	Push Y Min	-251.10	-0.2733	>CP
B20	Push Y Max	255.16	0.3299	>CP

Table 5.3: Beam rotations for RB-I Case 3 – column is removed from the long side (Gr1C) of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	396.65	0.2381	>CP	B11	Push Y Max	409.11	0.2725	>CP	B11	Push Y Max	404.11	0.2669	>CP
B11	Push Y Min	-409.60	-0.286	>CP	B11	Push Y Min	-413.3	-0.2795	>CP	B11	Push Y Min	-413.53	-0.2767	>CP
B15	Push Y Max	396.03	0.2337	>CP	B15	Push Y Max	409.18	0.2697	>CP	B15	Push Y Max	404.31	0.2673	>CP
B15	Push Y Min	-407.83	-0.2937	>CP	B15	Push Y Min	-412.29	-0.2835	>CP	B15	Push Y Min	-410.7	-0.2784	>CP
B16	Push Y Max	270.39	0.4824	>CP	B16	Push Y Max	271.07	0.4821	>CP	B16	Push Y Max	270.73	0.4822	>CP
B16	Push Y Min	-260.39	-0.4817	>CP	B16	Push Y Min	-266.7	-0.4827	>CP	B16	Push Y Min	-266.59	-0.4839	>CP
B17	Push Y Max	272.31	0.4838	>CP	B17	Push Y Max	272.94	0.4842	>CP	B17	Push Y Max	272.12	0.4834	>CP
B17	Push Y Min	-263.55	-0.4821	>CP	B17	Push Y Min	-270.41	-0.4826	>CP	B17	Push Y Min	-267.62	-0.4827	>CP
B19	Push Y Max	272.03	0.4816	>CP	B19	Push Y Max	272.82	0.4833	>CP	B19	Push Y Max	272.20	0.4834	>CP
B19	Push Y Min	-265.74	-0.4811	>CP	B19	Push Y Min	-270.28	-0.4819	>CP	B19	Push Y Min	-267.70	-0.4827	>CP
B20	Push Y Max	270.93	0.4832	>CP	B20	Push Y Max	271.33	0.4833	>CP	B20	Push Y Max	270.72	0.4823	>CP
B20	Push Y Min	-261.17	-0.4842	>CP	B20	Push Y Min	-266.97	-0.4839	>CP	B20	Push Y Min	-266.54	-0.4842	>CP

Table 5.3: (continued) Beam rotations for RB-I Case 3 – column is removed from the long side (Gr1C) of the building (Story 5, 4, 3 and 2).

Story 5					**Story 4**					**Story 3**				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	406.6	0.2636	>CP	B11	Push Y Max	404.15	0.2446	>CP	B11	Push Y Max	402.59	0.206	>CP
B11	Push Y Min	-412.06	-0.2707	>CP	B11	Push Y Min	-411.06	-0.254	>CP	B11	Push Y Min	-407.17	-0.2107	>CP
B15	Push Y Max	407.37	0.2637	>CP	B15	Push Y Max	404.61	0.2446	>CP	B15	Push Y Max	402.81	0.206	>CP
B15	Push Y Min	-413.73	-0.2706	>CP	B15	Push Y Min	-411.72	-0.2541	>CP	B15	Push Y Min	-407.51	-0.2107	>CP
B16	Push Y Max	267.11	0.4836	>CP	B16	Push Y Max	264.25	0.4828	>CP	B16	Push Y Max	259.68	0.4338	>CP
B16	Push Y Min	-263.55	-0.4839	>CP	B16	Push Y Min	-262.25	-0.483	>CP	B16	Push Y Min	-258.94	-0.433	>CP
B17	Push Y Max	269.86	0.4839	>CP	B17	Push Y Max	264.31	0.4832	>CP	B17	Push Y Max	257.27	0.3647	>CP
B17	Push Y Min	-266.72	-0.4836	>CP	B17	Push Y Min	-260.61	-0.4841	>CP	B17	Push Y Min	-256.27	-0.3659	>CP
B19	Push Y Max	269.82	0.4836	>CP	B19	Push Y Max	265.17	0.4833	>CP	B19	Push Y Max	257.99	0.3652	>CP
B19	Push Y Min	-266.67	-0.4834	>CP	B19	Push Y Min	-260.98	-0.4842	>CP	B19	Push Y Min	-256.77	-0.3663	>CP
B20	Push Y Max	267.22	0.482	>CP	B20	Push Y Max	266.72	0.4827	>CP	B20	Push Y Max	261.97	0.4332	>CP
B20	Push Y Min	-263.72	-0.4842	>CP	B20	Push Y Min	-262.81	-0.4828	>CP	B20	Push Y Min	-259.33	-0.4323	>CP
Story 2					**Story 2**									
B16	Push Y Max	255.81	0.3308	>CP	B19	Push Y Max	250.08	0.2726	>CP					
B16	Push Y Min	-254.1	-0.3305	>CP	B19	Push Y Min	-251.11	-0.2733	>CP					
B17	Push Y Max	252.26	0.2718	>CP	B20	Push Y Max	255.2	0.3299	>CP					
B17	Push Y Min	-251.49	-0.2726	>CP	B20	Push Y Min	-253.45	-0.3297	>CP					

Table 5.4: Beam rotations for RB-I Case 4 – column is removed from the corner of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	469.34	0.2373	>CP	B11	Push Y Max	502.06	0.2717	>CP	B11	Push Y Max	494.48	0.2662	>CP
B11	Push Y Min	-502.88	-0.2852	>CP	B11	Push Y Min	-495.78	-0.2788	>CP	B11	Push Y Min	-495.02	-0.2759	>CP
B15	Push Y Max	467.86	0.233	>CP	B15	Push Y Max	501.32	0.2691	>CP	B15	Push Y Max	495.11	0.2667	>CP
B15	Push Y Min	-498.06	-0.2927	>CP	B15	Push Y Min	-494.5	-0.283	>CP	B15	Push Y Min	-492.08	-0.2778	>CP
B16	Push Y Max	270.36	0.4824	>CP	B16	Push Y Max	271.05	0.4821	>CP	B16	Push Y Max	270.72	0.4822	>CP
B16	Push Y Min	-275.88	-0.4817	>CP	B16	Push Y Min	-266.69	-0.4827	>CP	B16	Push Y Min	-266.58	-0.4838	>CP
B17	Push Y Max	272.3	0.4838	>CP	B17	Push Y Max	272.93	0.4842	>CP	B17	Push Y Max	272.1	0.4834	>CP
B17	Push Y Min	-263.49	-0.4822	>CP	B17	Push Y Min	-270.4	-0.4826	>CP	B17	Push Y Min	-267.61	-0.4827	>CP
B19	Push Y Max	272.03	0.4816	>CP	B19	Push Y Max	272.82	0.4833	>CP	B19	Push Y Max	272.19	0.4834	>CP
B19	Push Y Min	-265.73	-0.4812	>CP	B19	Push Y Min	-270.28	-0.4819	>CP	B19	Push Y Min	-267.7	-0.4827	>CP
B20	Push Y Max	270.92	0.4832	>CP	B20	Push Y Max	271.32	0.4833	>CP	B20	Push Y Max	270.73	0.4823	>CP
B20	Push Y Min	-276.81	-0.4842	>CP	B20	Push Y Min	-266.97	-0.4839	>CP	B20	Push Y Min	-266.54	-0.4842	>CP

Table 5.4: (continued) Beam rotations for RB-I Case 4 – column is removed from the corner of the building (Story 5, 4 and 3).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	469.34	0.2373	>CP	B11	Push Y Max	502.06	0.2717	>CP	B11	Push Y Max	494.48	0.2662	>CP
B11	Push Y Min	-502.88	-0.2852	>CP	B11	Push Y Min	-495.78	-0.2788	>CP	B11	Push Y Min	-495.02	-0.2759	>CP
B15	Push Y Max	467.86	0.233	>CP	B15	Push Y Max	501.32	0.2691	>CP	B15	Push Y Max	495.11	0.2667	>CP
B15	Push Y Min	-498.06	-0.2927	>CP	B15	Push Y Min	-494.5	-0.283	>CP	B15	Push Y Min	-492.08	-0.2778	>CP
B16	Push Y Max	270.36	0.4824	>CP	B16	Push Y Max	271.05	0.4821	>CP	B16	Push Y Max	270.72	0.4822	>CP
B16	Push Y Min	-275.88	-0.4817	>CP	B16	Push Y Min	-266.69	-0.4827	>CP	B16	Push Y Min	-266.58	-0.4838	>CP
B17	Push Y Max	272.3	0.4838	>CP	B17	Push Y Max	272.93	0.4842	>CP	B17	Push Y Max	272.1	0.4834	>CP
B17	Push Y Min	-263.49	-0.4822	>CP	B17	Push Y Min	-270.4	-0.4826	>CP	B17	Push Y Min	-267.61	-0.4827	>CP
B19	Push Y Max	272.03	0.4816	>CP	B19	Push Y Max	272.82	0.4833	>CP	B19	Push Y Max	272.19	0.4834	>CP
B19	Push Y Min	-265.73	-0.4812	>CP	B19	Push Y Min	-270.28	-0.4819	>CP	B19	Push Y Min	-267.7	-0.4827	>CP
B20	Push Y Max	270.92	0.4832	>CP	B20	Push Y Max	271.32	0.4833	>CP	B20	Push Y Max	270.73	0.4823	>CP
B20	Push Y Min	-276.81	-0.4842	>CP	B20	Push Y Min	-266.97	-0.4839	>CP	B20	Push Y Min	-266.54	-0.4842	>CP

5.3.2 PC Potential of Regular Building with Truss Beams Due to Pushover Analysis, (RB-T)

Rotation's calculated for Regular Building, then compared for each element of the building with truss beams in this section. Table 5.5, Table 5.6 and Table 5.8 indicate that none of the Rotation's elements are more than 0.21. Therefore, any type of column removal from the first story did not cause risk of PC (Table 5.5, Table 5.6 and Table 5.8). As can be seen in Table 5.7, some of the beams achieved rotations >0.21.

Table 5.5: Beam rotations for RB-T Case 1 – column is removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	502.91	0.0737	>CP
Story8	B11	Push Y Min	-489.44	-0.1350	>CP

Table 5.6: Beam rotations for RB-T Case 2 – column is removed from the long side (Gr1B) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story7	B11	Push X Max	429.82	0.0262	IO to LS
Story7	B11	Push X Min	-435.97	-0.0275	IO to LS

Table 5.7: Beam rotations for RB-T Case 3 – column is removed from the long side (Gr1C) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B2	Push Y Max	387.69	0.4433	>CP
Story8	B2	Push Y Min	-381.82	-0.4438	>CP
Story8	B3	Push Y Max	391.75	0.4405	>CP
Story8	B3	Push Y Min	-380.71	-0.4405	>CP

Table 5.8: Beam rotations for RB-T Case 4 – column is removed from the corner of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push X Max	423.78	0.0200	IO to LS
Story8	B13	Push X Max	446.58	0.0348	IO to LS
Story8	B13	Push X Min	-445.22	-0.0346	IO to LS
Story8	B15	Push X Max	413.46	0.0131	IO to LS
Story8	B15	Push X Min	-420.91	-0.0172	IO to LS

5.4 Irregular Buildings, IR8F

Column removal locations as Case1, Case2, Case3 and Case4 are illustrated in Chapter 4, Figure 4.10, The rotation values obtained as a result of pushover analysis for the trusses are less than the rotation values of the I-beams for all IR8F. On the other hand, the rotation values for all the IR8F-I and IR8F-T columns are less than the values given by acceptance criteria. Therefore, the building with truss beams has lower potential for PC when a column is suddenly removed.

The I-beam rotation values for IR8F-I are greater than the rotation values for the top and bottom chords of the truss beam for IR8F-T. Hence, the building with a higher rotation value has higher risk of PC when a column is suddenly removed.

5.4.1 PC Potential of IR8F Building with I-Beams Due to Pushover Analysis, (IR8F-I)

Rotation's calculated for 8 Floors Irregular Building, then compared for each element of the building with I-beams in this section. Table 5.9 indicate that none of the rotation's elements are more than 0.21. As can be seen in Tables 5.10 to 5.12, some of the members achieved rotation >0.21.

Table 5.9: Beam rotations for IR8F-I Case 1 – column is removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	492.41	0.0870	>CP
Story8	B11	Push Y Min	-492.73	-0.1291	>CP

Table 5.10: Beam rotations for IR8F-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	352.93	0.3906	>CP	B11	Push Y Max	367.25	0.3992	>CP	B16	Push Y Max	252.25	0.4811	>CP
B11	Push Y Min	-328.61	-0.3988	>CP	B11	Push Y Min	-396.03	-0.4	>CP	B16	Push Y Min	-249.81	-0.4838	>CP
B15	Push Y Max	363.38	0.3844	>CP	B15	Push Y Max	359.07	0.3996	>CP	B17	Push Y Max	253.85	0.4842	>CP
B15	Push Y Min	-308.43	-0.4003	>CP	B15	Push Y Min	-373.95	-0.3989	>CP	B17	Push Y Min	-249.92	-0.4825	>CP
B16	Push Y Max	252.1	0.4817	>CP	B16	Push Y Max	253.62	0.482	>CP	B19	Push Y Max	253.95	0.4841	>CP
B16	Push Y Min	-244.28	-0.4819	>CP	B16	Push Y Min	-252.06	-0.4817	>CP	B19	Push Y Min	-250.03	-0.4825	>CP
B17	Push Y Max	253.66	0.4834	>CP	B17	Push Y Max	254.25	0.4824	>CP					
B17	Push Y Min	-247.36	-0.4807	>CP	B17	Push Y Min	-251.93	-0.4815	>CP					
B19	Push Y Max	253.48	0.4813	>CP	B19	Push Y Max	254.24	0.4815	>CP					
B19	Push Y Min	-247.11	-0.4829	>CP	B19	Push Y Min	-251.91	-0.4808	>CP					
B20	Push Y Max	252.43	0.484	>CP	B20	Push Y Max	253.75	0.4831	>CP					
B20	Push Y Min	-244.81	-0.4842	>CP	B20	Push Y Min	-252.2	-0.4828	>CP					

Table 5.10: (continued) Beam rotations for IR8F-I Case 2 – column is removed from the short side (Gr1B) of the building (Story 5, 4, 3 and 1).

Story 5

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	348.28	0.3741	>CP
B11	Push Y Min	-394.03	-0.3807	>CP
B16	Push Y Max	253.17	0.4833	>CP
B16	Push Y Min	-249.88	-0.4838	>CP
B20	Push Y Max	253.2	0.4836	>CP
B20	Push Y Min	-247.67	-0.484	>CP

Story 4

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B20	Push Y Max	251.7	0.4805	>CP
B20	Push Y Min	-247.81	-0.484	>CP

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B19	Push Y Max	246.71	0.4794	>CP
B19	Push Y Min	-245.58	-0.4815	>CP

Story 1

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	291.35	0.2322	>CP
B16	Push Y Min	-296.24	-0.2242	>CP
B17	Push Y Max	295.03	0.2152	>CP
B17	Push Y Min	-300.52	-0.2035	>CP
B19	Push Y Max	297.17	0.2166	>CP
B19	Push Y Min	-303.02	-0.2047	>CP

Table 5.11: Beam rotations for IR8F-I Case 3 – column is removed from the short side (Gr1C) of the building (Story 8, 7 and 5).

Story 8					Story 7					Story 5				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	369.95	0.3955	>CP	B11	Push Y Max	367.28	0.3969	>CP	B19	Push Y Max	251.18	0.482	>CP
B11	Push Y Min	-328.62	-0.3984	>CP	B11	Push Y Min	-396.03	-0.4	>CP	B19	Push Y Min	-249.8	-0.4832	>CP
B15	Push Y Max	377.4	0.3894	>CP	B15	Push Y Max	358.21	0.3992	>CP					
B15	Push Y Min	-307.74	-0.3994	>CP	B15	Push Y Min	-373.1	-0.3999	>CP					
B16	Push Y Max	252.05	0.4818	>CP	B16	Push Y Max	253.56	0.4837	>CP					
B16	Push Y Min	-244.23	-0.4819	>CP	B16	Push Y Min	-252.02	-0.4818	>CP					
B17	Push Y Max	253.63	0.484	>CP	B17	Push Y Max	254.23	0.4822	>CP					
B17	Push Y Min	-247.34	-0.4808	>CP	B17	Push Y Min	-251.91	-0.4816	>CP					
B19	Push Y Max	253.39	0.4817	>CP	B19	Push Y Max	254.14	0.4811	>CP					
B19	Push Y Min	-247.05	-0.4818	>CP	B19	Push Y Min	-251.82	-0.4808	>CP					
B20	Push Y Max	252.38	0.4841	>CP	B20	Push Y Max	253.70	0.4821	>CP					
B20	Push Y Min	-244.78	-0.4842	>CP	B20	Push Y Min	-252.18	-0.4829	>CP					

Table 5.11: (continued) Beam rotations for IR8F-I Case 3 – column is removed from the short side (Gr1C) of the building (Story 4, 3, 2 and 1).

Story 4

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	365.7	0.3541	>CP
B11	Push Y Min	-376.06	-0.3634	>CP
B15	Push Y Max	365.09	0.3533	>CP
B15	Push Y Min	-375.9	-0.3624	>CP
B16	Push Y Max	251.8	0.482	>CP
B16	Push Y Min	-248.08	-0.4841	>CP
B17	Push Y Max	250.4	0.4842	>CP
B17	Push Y Min	-246.47	-0.4821	>CP
B19	Push Y Max	250.4	0.484	>CP
B19	Push Y Min	-246.49	-0.482	>CP
B20	Push Y Max	251.71	0.482	>CP
B20	Push Y Min	-247.84	-0.4842	>CP

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B19	Push Y Max	246.69	0.4825	>CP
B19	Push Y Min	-245.56	-0.4811	>CP
B20	Push Y Max	247.57	0.4826	>CP
B20	Push Y Min	-246.42	-0.4826	>CP

Story 2

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	454.40	0.2270	>CP
B11	Push Y Min	-451.26	-0.2300	>CP

Story 1

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	295.46	0.2348	>CP
B16	Push Y Min	-300.31	-0.227	>CP
B17	Push Y Max	299.34	0.2179	>CP
B17	Push Y Min	-304.74	-0.2059	>CP
B19	Push Y Max	301.00	0.2191	>CP
B19	Push Y Min	-306.71	-0.2071	>CP
B20	Push Y Max	293.46	0.2332	>CP
B20	Push Y Min	-300.02	-0.2245	>CP

Table 5.12: Beam rotations for IR8F-I Case 4 – column is removed from the corner of the building (Story 8, 7 and 6).

Story 8					**Story 7**					**Story 6**				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	340.9	0.3985	>CP	B11	Push Y Max	366.11	0.3987	>CP	B11	Push Y Max	348.08	0.3981	>CP
B11	Push Y Min	-327.63	-0.3991	>CP	B11	Push Y Min	-394.83	-0.4	>CP	B11	Push Y Min	-393.76	-0.3991	>CP
B15	Push Y Max	349.41	0.3994	>CP	B15	Push Y Max	358.9	0.3984	>CP	B15	Push Y Max	348.75	0.3998	>CP
B15	Push Y Min	-308.24	-0.3987	>CP	B15	Push Y Min	-373.72	-0.3994	>CP	B15	Push Y Min	-391.49	-0.399	>CP
B17	Push Y Max	253.61	0.4833	>CP	B16	Push Y Max	253.55	0.4831	>CP	B16	Push Y Max	252.17	0.4811	>CP
B17	Push Y Min	-247.28	-0.4807	>CP	B16	Push Y Min	-252	-0.4817	>CP	B16	Push Y Min	-249.76	-0.4839	>CP
B19	Push Y Max	253.5	0.4813	>CP	B17	Push Y Max	254.14	0.4814	>CP	B17	Push Y Max	253.73	0.484	>CP
B19	Push Y Min	-247.08	-0.4798	>CP	B17	Push Y Min	-251.85	-0.4814	>CP	B17	Push Y Min	-249.79	-0.4824	>CP
B20	Push Y Max	252.45	0.484	>CP	B19	Push Y Max	254.21	0.4806	>CP	B19	Push Y Max	253.91	0.4842	>CP
B20	Push Y Min	-244.77	-0.4842	>CP	B19	Push Y Min	-251.89	-0.4808	>CP	B19	Push Y Min	-249.97	-0.4825	>CP
					B20	Push Y Max	253.71	0.4842	>CP	B20	Push Y Max	252.17	0.4811	>CP
					B20	Push Y Min	-252.17	-0.4828	>CP	B20	Push Y Min	-249.72	-0.4842	>CP

Table 5.12: (continued) Beam rotations for IR8F-I Case 4 – column is removed from the corner of the building (Story 5, 4, 3 and 1).

Story 5

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	253.11	0.4833	>CP
B16	Push Y Min	-249.85	-0.4838	>CP
B17	Push Y Max	251.2	0.4809	>CP
B17	Push Y Min	-249.87	-0.4841	>CP

Story 4

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B19	Push Y Max	250.4	0.4842	>CP
B19	Push Y Min	-246.41	-0.4829	>CP

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B15	Push Y Max	382.78	0.3104	>CP
B15	Push Y Min	-378.12	-0.3141	>CP
B16	Push Y Max	247.86	0.4832	>CP
B16	Push Y Min	-246.74	-0.4833	>CP
B20	Push Y Max	247.47	0.4821	>CP
B20	Push Y Min	-246.31	-0.4822	>CP

Story 1

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	287.54	0.2461	>CP
B16	Push Y Min	-293.49	-0.2377	>CP
B17	Push Y Max	291.44	0.2283	>CP
B17	Push Y Min	-297.49	-0.2159	>CP

5.4.2 PC Potential of IR8F Building with Truss Beam Due to Pushover Analysis, (IR8F-T)

Rotation's calculated for 8 Floors Irregular Building, then compared for each element of the building with truss beams in this section. Table 5.13 indicate that none of the rotation's elements are more than 0.21. In the short side of the building is not high. As can be seen in Tables 5.14 to 5.16, some of the members achieved rotations more than the accepted limits. In addition, Tables 5.14 to 5.16 shows increased risk of PC when column is removed from the long and corner sides of the IR8F-T

Table 5.13: Beam rotations for IR8F-T Case 1 – column is removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	502.94	0.0737	>CP
Story8	B11	Push Y Min	-486.14	-0.1323	>CP

Table 5.14: Beam rotations for IR8F-T Case 2 – column is removed from the long side (Gr1B) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	376.35	0.1590	>CP
Story8	B12	Push Y Max	390.23	0.1887	>CP

Table 5.15: Beam rotations for IR8F-T Case 3 – column is removed from the long side (Gr1C) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	376.35	0.1590	>CP
Story8	B12	Push Y Max	390.23	0.1887	>CP
Story8	B15	Push X Min	-421.76	-0.0178	IO to LS
Story8	B15	Push Y Max	412.78	0.0116	IO to LS
Story8	B15	Push Y Min	-424.72	-0.0218	IO to LS

Table 5.16: Beam rotations for IR8F-T Case 4 – column is removed from the corner of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push X Max	424.92	0.0190	IO to LS
Story8	B11	Push X Min	-413.73	-0.0139	IO to LS
Story8	B13	Push X Max	444.06	0.0356	IO to LS
Story8	B13	Push X Min	-446.89	-0.0350	IO to LS
Story8	B15	Push X Max	414.15	0.0129	IO to LS
Story8	B15	Push X Min	-420.86	-0.0171	IO to LS

5.5 Irregular Buildings, IR4F

Column removal locations as Case1, Case2, Case3 and Case4 are illustrated in Chapter 4, Figure 4.19, The rotation values obtained as a result of pushover analysis for the trusses are less than the rotation values of the I-beams for all IR4F. On the other hand, the rotation values for all the IR4F-I and IR4F-T columns are less than the values given by acceptance criteria. Therefore, the building with truss beams has lower potential for PC when a column is suddenly removed.

The rotation values of IR4F-I is more than the truss beam rotation values for truss members for IR4F-T.

5.5.1 PC Potential of IR4F Building with I-Beams Due to Pushover Analysis, (IR4F-I)

Beam rotations were calculated for 4 Floors Irregular Building, then compared for each element of the building with I-beams in this section. Table 5.17 indicate that none of the beam or column rotations are more than 0.21. Tables 5.18 to 5.20 shows that some of the beams achieved rotation more than the rotation value.

Table 5.17: Beam rotations for IR4F-I Case1 – column is removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	494.51	0.0817	>CP
Story8	B11	Push Y Min	-488.14	-0.1262	>CP

Table 5.18: Beam rotations for IR4F-I Case 2 – column is removed from the long side (Gr1B) of the building.

Story 8

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	396.66	0.2333	>CP
B11	Push Y Min	-409.62	-0.2813	>CP
B15	Push Y Max	396.03	0.2284	>CP
B15	Push Y Min	-407.85	-0.2863	>CP
B16	Push Y Max	270.26	0.481	>CP
B16	Push Y Min	-260.28	-0.4809	>CP
B17	Push Y Max	272.06	0.4836	>CP
B17	Push Y Min	-265.4	-0.4822	>CP
B19	Push Y Max	271.72	0.4814	>CP
B19	Push Y Min	-265.01	-0.4811	>CP
B20	Push Y Max	270.78	0.4834	>CP
B20	Push Y Min	-261.05	-0.4834	>CP

Story 7

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B19	Push Y Max	272.53	0.4833	>CP
B19	Push Y Min	-269.99	-0.4819	>CP
B20	Push Y Max	271.23	0.4834	>CP
B20	Push Y Min	-268.69	-0.4841	>CP

Story 6

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B20	Push Y Max	270.58	0.4828	>CP
B20	Push Y Min	-266.42	-0.4822	>CP

Story 5

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	268.31	0.4833	>CP
B16	Push Y Min	-264.10	-0.4839	>CP
B20	Push Y Max	268.40	0.4836	>CP
B20	Push Y Min	-264.20	-0.4842	>CP

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	255.70	0.3233	>CP
B16	Push Y Min	-253.95	-0.3227	>CP

Table 5.19: Beam rotations for IR4F-I Case 3 – column is removed from the long side (Gr1C) of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	396.66	0.2333	>CP	B20	Push Y Max	271.23	0.4834	>CP	B20	Push Y Max	270.59	0.4831	>CP
B11	Push Y Min	-409.63	-0.2813	>CP	B20	Push Y Min	-268.69	-0.4841	>CP	B20	Push Y Min	-266.43	-0.4842	>CP
B15	Push Y Max	396.03	0.2284	>CP										
B15	Push Y Min	-407.85	-0.2863	>CP										
B16	Push Y Max	270.26	0.4809	>CP										
B16	Push Y Min	-260.28	-0.4808	>CP										
B17	Push Y Max	272.06	0.4842	>CP										
B17	Push Y Min	-265.4	-0.4827	>CP										
B19	Push Y Max	271.72	0.482	>CP										
B19	Push Y Min	-265.01	-0.4817	>CP										
B20	Push Y Max	270.78	0.4834	>CP										
B20	Push Y Min	-261.06	-0.4834	>CP										

Table 5.19: (continued) Beam rotations for IR4F-I Case 3 – column is removed from the long side (Gr1C) of the building (Story 5, 4 and 3).

Story 5					Story 4					Story 3				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	406.56	0.2572	>CP	B11	Push Y Max	404.18	0.2116	>CP	B16	Push Y Max	255.69	0.3232	>CP
B11	Push Y Min	-412.13	-0.265	>CP	B11	Push Y Min	-408.27	-0.2147	>CP	B16	Push Y Min	-253.94	-0.3225	>CP
B15	Push Y Max	407.21	0.2572	>CP	B15	Push Y Max	404.32	0.2115	>CP					
B15	Push Y Min	-413.67	-0.2648	>CP	B15	Push Y Min	-408.44	-0.2147	>CP					
B16	Push Y Max	268.31	0.4832	>CP	B16	Push Y Max	261.38	0.4298	>CP					
B16	Push Y Min	-264.10	-0.4839	>CP	B16	Push Y Min	-257.46	-0.429	>CP					
B17	Push Y Max	269.55	0.4834	>CP	B17	Push Y Max	256.12	0.3489	>CP					
B17	Push Y Min	-266.41	-0.4835	>CP	B17	Push Y Min	-255.97	-0.3525	>CP					
B19	Push Y Max	269.51	0.4832	>CP	B19	Push Y Max	256.40	0.3494	>CP					
B19	Push Y Min	-266.37	-0.4834	>CP	B19	Push Y Min	-256.29	-0.3529	>CP					
B20	Push Y Max	268.40	0.4836	>CP	B20	Push Y Max	261.08	0.4292	>CP					
B20	Push Y Min	-264.21	-0.4842	>CP	B20	Push Y Min	-259.52	-0.4284	>CP					

Table 5.20: Beam rotations for IR4F-I Case 4 – column is removed from the corner of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	469.38	0.2324	>CP	B11	Push Y Max	502.74	0.2669	>CP	B15	Push Y Max	496.19	0.2627	>CP
B11	Push Y Min	-502.65	-0.2805	>CP	B11	Push Y Min	-495.68	-0.2738	>CP	B15	Push Y Min	-493.12	-0.2737	>CP
B15	Push Y Max	467.73	0.2281	>CP	B15	Push Y Max	497.21	0.2648	>CP	B16	Push Y Max	270.6	0.4811	>CP
B15	Push Y Min	-498.05	-0.286	>CP	B15	Push Y Min	-495.01	-0.2785	>CP	B16	Push Y Min	-266.47	-0.4832	>CP
B16	Push Y Max	270.23	0.4811	>CP	B16	Push Y Max	270.95	0.4827	>CP	B17	Push Y Max	271.8	0.4832	>CP
B16	Push Y Min	-276.89	-0.4825	>CP	B16	Push Y Min	-268.38	-0.483	>CP	B17	Push Y Min	-268.37	-0.4827	>CP
B17	Push Y Max	272.06	0.4821	>CP	B17	Push Y Max	272.65	0.4828	>CP	B19	Push Y Max	271.93	0.4834	>CP
B17	Push Y Min	-265.37	-0.4835	>CP	B17	Push Y Min	-270.12	-0.4838	>CP	B19	Push Y Min	-268.51	-0.4827	>CP
B19	Push Y Max	271.76	0.4839	>CP	B19	Push Y Max	272.58	0.482	>CP	B20	Push Y Max	270.61	0.4842	>CP
B19	Push Y Min	-265.02	-0.4827	>CP	B19	Push Y Min	-270.04	-0.4832	>CP	B20	Push Y Min	-266.45	-0.4835	>CP
B20	Push Y Max	270.78	0.4834	>CP	B20	Push Y Max	271.23	0.4816	>CP					
B20	Push Y Min	-277.83	-0.4828	>CP	B20	Push Y Min	-268.69	-0.4842	>CP					

Table 5.20: (continued) Beam rotations for IR4F-I Case 4 – column is removed from the corner of the building (Story 5 and 3).

Story 5					Story 3				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	495.32	0.2565	>CP	B16	Push Y Max	275.23	0.4291	>CP
B11	Push Y Min	-496.1	-0.2643	>CP	B16	Push Y Min	-277.12	-0.4283	>CP
B15	Push Y Max	497.31	0.257	>CP	B17	Push Y Max	295.21	0.3482	>CP
B15	Push Y Min	-498.94	-0.2646	>CP	B17	Push Y Min	-297.12	-0.3518	>CP
B16	Push Y Max	268.31	0.4832	>CP	B20	Push Y Max	274.87	0.4283	>CP
B16	Push Y Min	-264.1	-0.4839	>CP	B20	Push Y Min	-279.3	-0.4276	>CP
B19	Push Y Max	269.54	0.4834	>CP	B16	Push Y Max	275.23	0.4291	>CP
B19	Push Y Min	-266.41	-0.4836	>CP	B16	Push Y Min	-277.12	-0.4283	>CP
B20	Push Y Max	268.42	0.4818	>CP					
B20	Push Y Min	-264.23	-0.4842	>CP					

5.5.2 PC Potential of IR4F Building with Truss Beams Due to Pushover Analysis, (IR4F-T)

Rotation's calculated for 4 Floors Irregular Building, then compared for each element of the building with truss beams in this section. According to Tables 5.21, 5.22 and 5.24 none of the member rotations are more than 0.21 radian. As can be seen in Table 5.23, some of the members achieved rotations >0.21 radian.

Table 5.21: Beam rotations for IR4F-T Case 1- column is removed from the short side of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push Y Max	502.94	0.0737	>CP
Story8	B11	Push Y Min	-487.57	-0.1356	>CP

Table 5.22: Beam rotations for IR4F-T Case 2 – column is removed from the long side (Gr1B)of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B11	Push X Max	423.29	0.0199	IO to LS
Story8	B11	Push X Min	-415.73	-0.0135	IO to LS
Story8	B13	Push X Max	446.10	0.0345	IO to LS
Story8	B13	Push X Min	-444.42	-0.0343	IO to LS
Story8	B18	Push X Max	247.47	0.0085	A to IO
Story8	B18	Push X Min	-247.56	-0.0085	A to IO

Table 5.23: Beam rotations for IR4F-T Case 3 – column is removed from the short side (Gr1C) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B12	Push Y Max	333.59	0.4438	>CP
Story8	B12	Push Y Min	-325.04	-0.4424	>CP
Story8	B13	Push Y Max	332.81	0.4409	>CP
Story8	B13	Push Y Min	-325.25	-0.4438	>CP
Story8	B16	Push Y Max	302.23	0.1442	>CP
Story8	B17	Push Y Max	306.18	0.1502	>CP
Story8	B17	Push Y Min	-299.31	-0.1368	>CP
Story8	B19	Push Y Max	306.51	0.1475	>CP
Story8	B19	Push Y Min	-298.51	-0.1393	>CP
Story8	B20	Push Y Max	306.21	0.1474	>CP
Story8	B20	Push Y Min	-307.58	-0.0889	>CP

Table 5.24: Beam rotations for IR4F-T Case 4 – column is removed from the corner of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story5	B16	Push X Max	252.83	0.0148	IO to LS
Story5	B16	Push X Min	-256.30	-0.0195	IO to LS
Story5	B18	Push X Max	262.22	0.0280	IO to LS
Story5	B18	Push X Min	-261.99	-0.0281	IO to LS
Story5	B19	Push X Max	250.93	0.0100	IO to LS
Story5	B19	Push X Min	-250.81	-0.0098	A to IO

5.6 Base Force and Monitored Displacement for Buildings

Once the yield rotation is achieved this means that the entire cross section has been yielded. Then the plastic rotation θ_p occurs, which is typically associated with a discrete plastic hinge that is inserted into a numerical frame model. The plastic hinge measures elastic and plastic rotations, although for simplicity, the elastic portion is ignored due to its small size. In addition, Table 5.25 and Table 5.26 are shown that base force versus monitored displacement x and y direction for Regular Buildings, IR8F Buildings and IR4F Buildings.

Table 5.25: Base force versus monitored displacement in x direction.

Build. Types	Comp.	Case	Monitored Displ. (mm)	Base Force (kN)	A-IO	IO-LS	LS-CP	>CP	Total Hinges
REGULAR	I-Beam	1	-1056	38821.844	664	35	177	0	876
		2	-1056	40321.0289	665	29	184	0	878
		3	-1056	40326.1764	666	28	184	0	878
		4	-1056	39716.0871	679	29	170	0	878
	Truss Beam	1	-1056	38791.0175	3530	34	186	0	3750
		2	-1056	39269.7453	3531	41	182	0	3754
		3	-1056	39194.0622	3529	43	182	0	3754
		4	-1056	39402.1068	3539	36	179	0	3754
IR8F	I-Beam	1	-1056	39161.7719	648	29	167	0	844
		2	-1056	40156.0661	650	26	170	0	846
		3	-1056	39482.7133	663	27	156	0	846
		4	-1056	39578.3714	663	27	156	0	846
	Truss Beam	1	-1056	38826.482	3514	25	179	0	3718
		2	-1056	39045.6637	3516	28	178	0	3722
		3	-1056	38548.5956	3526	34	162	0	3722
		4	-1056	39185.2193	3518	35	169	0	3722
IR4F	I-Beam	1	-1056	37495.1173	658	34	172	0	864
		2	-1056	38950.5274	659	29	178	0	866
		3	-1056	38843.1245	660	41	165	0	866
		4	-1056	38368.1243	673	29	164	0	866
	Truss Beam	1	-1056	37478.6818	3524	32	182	0	3738
		2	-1056	37927.1679	3523	38	181	0	3742
		3	-1056	37750.33	3527	34	181	0	3742
		4	-1056	38055.2443	3532	37	173	0	3742

Table 5.26: Base force versus monitored displacement in y direction.

Build. Types	Comp.	Case	Monitored Displ. (mm)	Base Force (kN)	A-IO	IO-LS	LS-CP	>CP	Total Hinges
REGULAR	I-Beam	1	-1056	38821.844	664	35	177	0	876
		2	1.2	1775823	741	3	13	121	878
		3	-1056	40326.1764	666	28	184	0	878
		4	14.5	1771871	741	3	13	121	878
	Truss Beam	1	672.4	142682.6494	3550	78	106	16	3750
		2	0.4	71612.0106	3724	30	0	0	3754
		3	85.4	561413.4935	3455	50	171	78	3754
		4	4.1	53825.3224	3747	7	0	0	3754
IR8F	I-Beam	1	801.1	70654.8686	697	38	92	17	844
		2	219.9	2356076	646	29	45	126	846
		3	230.1	2381214	644	30	47	125	846
		4	224.1	2485988	641	32	43	130	846
	Truss Beam	1	-1056	38826.482	3514	25	179	0	3718
		2	30.6	330530.4243	3464	62	165	31	3722
		3	61.2	279173.2009	3506	62	138	16	3722
		4	6.6	55557.9462	3710	12	0	0	3722
IR4F	I-Beam	1	756.3	69720.1572	706	41	100	17	864
		2	16	1675951	693	20	34	119	866
		3	16.5	1675939	693	20	34	119	866
		4	13.1	1673314	692	19	36	119	866
	Truss Beam	1	679.5	137199.8097	3549	71	102	16	3738
		2	0.2	53456.8784	3741	1	0	0	3742
		3	85.3	533300.2615	3447	52	173	70	3742
		4	4.1	51267.0117	3735	7	0	0	3742

5.7 Rehabilitation of Regular Buildings, (RB)

According to the analysis results, the failed beams and columns were located and then the rehabilitation plans was applied. The rehabilitation is carried out by replacing the column removed with a system of bracing members to resist the loads that caused the failure. Due to the behaviour mechanism of the bracings, the relocated bracings will transfer the loads coming from the upper beams to the lower column in the neighbouring bay. The connection type which is used in this situation is very crucial, both for the load transfer mechanism and for the column section behaviour.

5.7.1 Rehabilitation of Regular Building with I-Beams Due to Pushover Analysis, (RB-I)

Table 5.27: Beam rotations after rehabilitating RB-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	434.36	0.0282	IO to LS	B11	Push Y Max	446.04	0.0344	IO to LS	B11	Push Y Max	453.71	0.0396	IO to LS
B11	Push Y Min	427.16	-0.0223	IO to LS	B11	Push Y Min	-445.56	-0.036	IO to LS	B11	Push Y Min	-453.3	-0.0407	IO to LS
B15	Push Y Max	426.18	0.0208	IO to LS	B15	Push Y Max	448.32	0.0361	IO to LS	B15	Push Y Max	454.65	0.0402	IO to LS
B15	Push Y Min	433.93	-0.0257	IO to LS	B15	Push Y Min	-440.51	-0.0317	IO to LS	B15	Push Y Min	-450.12	-0.039	IO to LS
B16	Push Y Max	249.56	0.0102	IO to LS	B17	Push Y Max	250.93	0.0119	IO to LS	B16	Push Y Max	271.09	0.0375	IO to LS
B16	Push Y Min	-257.42	-0.021	IO to LS	B17	Push Y Min	-252.61	-0.012	IO to LS	B16	Push Y Min	-275.07	-0.0429	IO to LS
B17	Push Y Max	0	0	A to IO	B19	Push Y Max	252.63	0.0127	IO to LS	B17	Push Y Max	253.47	0.0164	IO to LS
B17	Push Y Min	-41.12	0	A to IO	B19	Push Y Min	-252.08	-0.0118	IO to LS	B17	Push Y Min	-255.54	-0.0178	IO to LS
B20	Push Y Max	259.63	0.0218	IO to LS	B20	Push Y Max	270.7	0.0386	IO to LS	B19	Push Y Max	256.75	0.0179	IO to LS
B20	Push Y Min	-251.1	-0.0102	IO to LS	B20	Push Y Min	-265.61	-0.033	IO to LS	B19	Push Y Min	-254.65	-0.0164	IO to LS
										B20	Push Y Max	272.79	0.0434	IO to LS
										B20	Push Y Min	-271.2	-0.0376	IO to LS

Table 5.27: (continued) Beam rotations after rehabilitating RB-I Case 2 – column is removed from the long side (Gr1B) of the building (Story5,4and2).

Story 5					Story 4					Story 2				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	458.55	0.0443	IO to LS	B11	Push Y Max	458.7	0.0462	IO to LS	B16	Push Y Max	283.36	0.0551	IO to LS
B11	Push Y Min	-461.02	-0.0454	IO to LS	B11	Push Y Min	-464.31	-0.0476	IO to LS	B16	Push Y Min	-283.4	-0.0554	IO to LS
B15	Push Y Max	460.03	0.0453	IO to LS	B15	Push Y Max	463.64	0.0474	IO to LS	B17	Push Y Max	278.84	0.0471	IO to LS
B15	Push Y Min	-460.06	-0.0443	IO to LS	B15	Push Y Min	-459.03	-0.0461	IO to LS	B17	Push Y Min	-275.96	-0.0463	IO to LS
B16	Push Y Max	272.61	0.0417	IO to LS	B16	Push Y Max	273.61	0.0411	IO to LS	B19	Push Y Max	275.85	0.0463	IO to LS
B16	Push Y Min	-277.69	-0.0485	IO to LS	B16	Push Y Min	-280.59	-0.0513	IO to LS	B19	Push Y Min	-276.88	-0.0474	IO to LS
B17	Push Y Max	257.82	0.0206	IO to LS	B17	Push Y Max	257.75	0.0226	IO to LS	B20	Push Y Max	284.77	0.0555	IO to LS
B17	Push Y Min	-260.45	-0.0229	IO to LS	B17	Push Y Min	-261.59	-0.0245	IO to LS	B20	Push Y Min	-284.48	-0.0551	IO to LS
B19	Push Y Max	258.68	0.0233	IO to LS	B19	Push Y Max	260.96	0.0255	IO to LS					
B19	Push Y Min	-258.12	-0.0207	IO to LS	B19	Push Y Min	-258.6	-0.0226	IO to LS					
B20	Push Y Max	279.29	0.0486	IO to LS	B20	Push Y Max	281.3	0.0514	IO to LS					
B20	Push Y Min	-273.85	-0.0419	IO to LS	B20	Push Y Min	-272.17	-0.0422	IO to LS					

Table 5.28: Beam rotations after rehabilitating RB-I Case 3 – column is removed from the long side (Gr1C) of the building (Story8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	435.09	0.0277	IO to LS	B15	Push Y Max	446.95	0.0352	IO to LS	B11	Push Y Max	453.75	0.0396	IO to LS
B11	Push Y Min	-425.27	-0.0201	IO to LS	B15	Push Y Min	-440.53	-0.0308	IO to LS	B11	Push Y Min	-451.9	-0.0404	IO to LS
B15	Push Y Max	426.1	0.0208	IO to LS	B16	Push Y Max	268.28	0.0356	IO to LS	B15	Push Y Max	453.95	0.0398	IO to LS
B15	Push Y Min	-430.65	-0.0251	IO to LS	B16	Push Y Min	-271.6	-0.0417	IO to LS	B15	Push Y Min	-447.92	-0.0386	IO to LS
B16	Push Y Max	251.37	0.0125	IO to LS	B17	Push Y Max	252.35	0.0123	IO to LS	B17	Push Y Max	254.74	0.0172	IO to LS
B16	Push Y Min	-260.53	-0.0244	IO to LS	B17	Push Y Min	-252.4	-0.0132	IO to LS	B17	Push Y Min	-256.83	-0.0188	IO to LS
B17	Push Y Max	31.22	0	A to IO	B19	Push Y Max	253.3	0.0132	IO to LS	B19	Push Y Max	255.41	0.0193	IO to LS
B17	Push Y Min	-40.89	0	A to IO	B19	Push Y Min	-251.15	-0.0126	IO to LS	B19	Push Y Min	-255.14	-0.0172	IO to LS
B19	Push Y Max	0	0	A to IO	B20	Push Y Max	272.66	0.0417	IO to LS	B20	Push Y Max	276.82	0.0465	IO to LS
B19	Push Y Max	41.64	0	A to IO	B20	Push Y Min	-269.27	-0.0357	IO to LS	B20	Push Y Min	-271.39	-0.0413	IO to LS
B20	Push Y Max	261.58	0.0245	IO to LS										
B20	Push Y Min	-252.36	-0.0125	IO to LS										

Table 5.28: (continued) Beam rotations after rehabilitating RB-I Case 3 – column is removed from the long side (Gr1C) of the building (Story5,4and2).

Story 5					Story 4					Story 2				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	460.86	0.0445	IO to LS	B11	Push Y Max	461.82	0.047	IO to LS	B11	Push Y Max	471.6	0.0521	IO to LS
B11	Push Y Min	-459.99	-0.0457	IO to LS	B11	Push Y Min	-463.49	-0.0484	IO to LS	B11	Push Y Min	-472.1	-0.0522	IO to LS
B15	Push Y Max	461.85	0.0452	IO to LS	B15	Push Y Max	462.4	0.0482	IO to LS	B15	Push Y Max	469.75	0.052	IO to LS
B15	Push Y Min	-459.09	-0.0444	IO to LS	B15	Push Y Min	-463.65	-0.046	IO to LS	B15	Push Y Min	-468.91	-0.0519	IO to LS
B16	Push Y Max	274.04	0.0451	IO to LS	B16	Push Y Max	274.13	0.0437	IO to LS	B16	Push Y Max	285.73	0.0574	IO to LS
B16	Push Y Min	-279.55	-0.0523	IO to LS	B16	Push Y Min	-282.54	-0.055	IO to LS	B16	Push Y Min	-286.44	-0.0588	IO to LS
B17	Push Y Max	258.43	0.0224	IO to LS	B17	Push Y Max	259.52	0.0225	IO to LS	B17	Push Y Max	275.7	0.0461	IO to LS
B17	Push Y Min	-260.63	-0.0243	IO to LS	B17	Push Y Min	-261.47	-0.0252	IO to LS	B17	Push Y Min	-275.63	-0.0441	IO to LS
B19	Push Y Max	260.66	0.0232	IO to LS	B19	Push Y Max	262.2	0.0253	IO to LS	B19	Push Y Max	276.66	0.0442	IO to LS
B19	Push Y Min	-259.28	-0.0224	IO to LS	B19	Push Y Min	-260.15	-0.0225	IO to LS	B19	Push Y Min	-276.39	-0.0461	IO to LS
B20	Push Y Max	280.49	0.0523	IO to LS	B20	Push Y Max	283.17	0.0551	IO to LS	B20	Push Y Max	287.06	0.0588	IO to LS
B20	Push Y Min	-274.2	-0.044	IO to LS	B20	Push Y Min	-274.81	-0.0438	IO to LS	B20	Push Y Min	-284.2	-0.0577	IO to LS

Table 5.29: Beam rotations after rehabilitating RB-I Case 4 – column is removed from the corner of the building (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	432.3	0.0257	IO to LS	B11	Push Y Max	441.47	0.0313	IO to LS	B11	Push Y Max	445.88	0.0342	IO to LS
B11	Push Y Min	-423.06	-0.0203	IO to LS	B11	Push Y Min	-443.65	-0.0328	IO to LS	B11	Push Y Min	-445.8	-0.0342	IO to LS
B15	Push Y Max	422.47	0.0204	IO to LS	B15	Push Y Max	353.72	0.0029	A to IO	B15	Push Y Max	443.6	0.0342	IO to LS
B15	Push Y Min	-427.23	-0.0236	IO to LS	B15	Push Y Min	-372.12	0.0021	A to IO	B15	Push Y Min	-440.67	-0.033	IO to LS
B16	Push Y Max	252.81	0.015	IO to LS	B17	Push Y Max	256.02	0.0169	IO to LS	B17	Push Y Max	245.81	0.003	A to IO
B16	Push Y Min	-245.25	-0.0022	A to IO	B17	Push Y Min	-253.59	-0.0136	IO to LS	B17	Push Y Min	-246.07	-0.0033	A to IO
B17	Push Y Max	255.48	0.0161	IO to LS	B19	Push Y Max	255.23	0.0168	IO to LS	B19	Push Y Max	245.49	0.0033	A to IO
B17	Push Y Min	-247.26	-0.008	A to IO	B19	Push Y Min	-252.72	-0.0135	IO to LS	B19	Push Y Min	-245.17	-0.003	A to IO
B19	Push Y Max	254.8	0.0161	IO to LS	B20	Push Y Max	255.18	0.015	IO to LS	B20	Push Y Max	250.32	0.0107	IO to LS
B19	Push Y Min	-249.2	-0.0076	A to IO	B20	Push Y Min	-251.57	-0.0129	IO to LS	B20	Push Y Min	-246.69	-0.0062	A to IO
B20	Push Y Max	254.71	0.0151	IO to LS										
B20	Push Y Min	-245.56	-0.0026	A to IO										

Table 5.29: (continued) Beam rotations after rehabilitating RB-I Case 4 – column is removed from the corner of the building (Story5,4 and 2).

Story 5					Story 4					Story 2				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	448.71	0.0362	IO to LS	B11	Push Y Max	447.56	0.0356	IO to LS	B11	Push Y Max	451.10	0.0386	IO to LS
B11	Push Y Min	-445.72	-0.0368	IO to LS	B11	Push Y Min	-449.56	-0.0369	IO to LS	B11	Push Y Min	-452.88	-0.0385	IO to LS
B15	Push Y Max	445.41	0.0367	IO to LS	B15	Push Y Max	449.78	0.0369	IO to LS	B15	Push Y Max	453.30	0.0385	IO to LS
B15	Push Y Min	-446.04	-0.0365	IO to LS	B15	Push Y Min	-447.81	-0.035	IO to LS	B15	Push Y Min	-451.51	-0.0386	IO to LS
B19	Push Y Max	247.07	0.0073	A to IO	B17	Push Y Max	247.40	0.0080	A to IO	B17	Push Y Max	257.89	0.0210	IO to LS
B19	Push Y Min	-248.39	-0.0069	A to IO	B17	Push Y Min	-248.37	-0.0094	A to IO	B17	Push Y Min	-256.33	-0.0194	IO to LS
B20	Push Y Max	253.26	0.0143	IO to LS	B19	Push Y Max	248.51	0.0094	A to IO	B19	Push Y Max	256.51	0.0194	IO to LS
B20	Push Y Min	-249.13	-0.0098	A to IO	B19	Push Y Min	-247.44	-0.0085	A to IO	B19	Push Y Min	-257.93	-0.0210	IO to LS
					B20	Push Y Max	256.18	0.0171	IO to LS	B20	Push Y Max	250.01	0.0086	A to IO
					B20	Push Y Min	-252.02	-0.0114	IO to LS	B20	Push Y Min	-247.55	-0.0053	A to IO

5.7.2 Rehabilitation of Regular Building with Truss Beams Due to Pushover Analysis, (RB-T)

The failed beams are located and rehabilitation plans have been applied for Case3.

Table 5.30: Beam rotations after rehabilitating RB-T Case 3 – column is removed from the long side (Gr1C) of the building

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B2	Push Y Max	30.72	0.0019	A to IO
Story8	B2	Push Y Min	-47.41	0.0012	A to IO
Story8	B3	Push Y Max	24.76	0.0012	A to IO
Story8	B3	Push Y Min	-25.56	0.0010	A to IO

5.8 Rehabilitation of Irregular Buildings, (IR8F)

The failed beams and columns were located and the rehabilitation plan was applied. The column removed was replaced by a system of bracing members to resist the failure loads. The relocated bracings were transferring the loads coming from the upper beams to the lower column in the neighbouring bay.

5.8.1 Rehabilitation of IR8F Building with I-Beams Due to Pushover Analysis, (IR8F-I)

The failed beams are located and rehabilitation plans have been applied for Case2, Case3 and Case4.

.

Table 5.31: Beam rotations after rehabilitating IR8F-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 8, 7 and 6).

Story 8				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	439.06	0.0296	IO to LS
B11	Push Y Min	-427.92	-0.0222	IO to LS
B15	Push Y Max	425.42	0.0225	IO to LS
B15	Push Y Min	-433.87	-0.0264	IO to LS
B16	Push Y Max	252.35	0.0121	IO to LS
B16	Push Y Min	-261.06	-0.0253	IO to LS
B19	Push Y Max	43.28	0.0021	A to IO
B19	Push Y Min	-34.64	0.0018	A to IO
B20	Push Y Max	261	0.0256	IO to LS
B20	Push Y Min	-252.47	-0.012	IO to LS

Story 7				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B15	Push Y Max	449.4	0.0374	IO to LS
B15	Push Y Min	-442.99	-0.0325	IO to LS
B16	Push Y Max	268.78	0.0367	IO to LS
B16	Push Y Min	-274.63	-0.0426	IO to LS
B17	Push Y Max	253.19	0.013	IO to LS
B17	Push Y Min	-254.36	-0.0146	IO to LS
B19	Push Y Max	254.45	0.0147	IO to LS
B19	Push Y Min	-252.9	-0.0134	IO to LS
B20	Push Y Max	274.25	0.0426	IO to LS
B20	Push Y Min	-270.47	-0.0366	IO to LS

Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B17	Push Y Max	255.74	0.0165	IO to LS
B17	Push Y Min	-256.46	-0.0199	IO to LS
B19	Push Y Max	257.92	0.0195	IO to LS
B19	Push Y Min	-254.95	-0.0174	IO to LS

Table 5.31: (continued) Beam rotations after rehabilitating IR8F-I Case 2 – column is removed from the long side (Gr1B) of the building (Story 5, 4, 2 and 1).

Story 5				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B16	Push Y Max	275.75	0.0456	IO to LS
B16	Push Y Min	-282.41	-0.0529	IO to LS
B20	Push Y Max	280.37	0.0531	IO to LS
B20	Push Y Min	-275.28	-0.0447	IO to LS

Story 4				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B20	Push Y Max	283.17	0.0558	IO to LS
B20	Push Y Min	-274.92	-0.0443	IO to LS
Story 1				
B19	Push Y Max	276.34	0.045	IO to LS
B19	Push Y Min	-278.36	-0.0466	IO to LS

Story 1				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B16	Push Y Max	282.3	0.0535	IO to LS
B16	Push Y Min	-283.16	-0.0547	IO to LS
B17	Push Y Max	281.04	0.0501	IO to LS
B17	Push Y Min	-277.4	-0.0481	IO to LS
B19	Push Y Max	277.4	0.0462	IO to LS
B19	Push Y Min	-277.96	-0.0492	IO to LS

Table 5.32: Beam rotations after rehabilitating IR8F-I Case 3 – column is removed from the long side (Gr1C) of the building (Story 8, 7 and 5).

Story 8					Story 7					Story 5				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	429.86	0.0262	IO to LS	B15	Push Y Max	437.9	0.0320	IO to LS	B19	Push Y Max	249.51	0.0080	A to IO
B11	Push Y Min	-426.10	-0.0202	IO to LS	B15	Push Y Min	-436.07	-0.0277	IO to LS	B19	Push Y Min	-247.69	-0.0077	A to IO
B15	Push Y Max	422.92	0.0186	IO to LS	B16	Push Y Max	245.3	0.0032	A to IO					
B15	Push Y Min	-428.42	-0.0224	IO to LS	B16	Push Y Min	-248.37	-0.0086	A to IO					
B16	Push Y Max	190.59	0.0025	A to IO	B17	Push Y Max	241.08	0.0020	A to IO					
B16	Push Y Min	-203.35	0.002	A to IO	B17	Push Y Min	-240.6	0.0012	A to IO					
B17	Push Y Max	31.18	0.0018	A to IO	B19	Push Y Max	244.19	0.0005	A to IO					
B17	Push Y Min	-83.55	0.002	A to IO	B19	Push Y Min	-242.73	-0.0007	A to IO					
B19	Push Y Max	85.80	0.0017	A to IO	B20	Push Y Max	250.72	0.0097	A to IO					
B19	Push Y Min	-31.75	0.0012	A to IO	B20	Push Y Min	-246.76	-0.0043	A to IO					

Table 5.32: (continued) Beam rotations after rehabilitating IR8F-I Case 3 – column is removed from the long side (Gr1C) of the building. (Story 4, 3, 2 and 1).

Story 4

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	448.11	0.0355	IO to LS
B11	Push Y Min	-449.95	-0.037	IO to LS
B15	Push Y Max	450	0.037	IO to LS
B15	Push Y Min	-447.3	-0.0358	IO to LS
B16	Push Y Max	251.51	0.0127	IO to LS
B16	Push Y Min	-254.88	-0.0181	IO to LS
B17	Push Y Max	249.13	0.009	A to IO
B17	Push Y Min	-251.05	-0.0101	IO to LS
B19	Push Y Max	250.93	0.01	IO to LS
B19	Push Y Min	-249.44	-0.009	A to IO
B20	Push Y Max	255.02	0.0185	IO to LS
B20	Push Y Min	-251.58	-0.0126	IO to LS

Story 3

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B20	Push Y Max	259.35	0.0228	IO to LS
B20	Push Y Min	-259.34	-0.024	IO to LS

Story 2

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B17	Push Y Min	-259.39	-0.0235	IO to LS
B11	Push Y Max	452.44	0.037	IO to LS
B11	Push Y Min	-452.5	-0.0389	IO to LS

Story 1

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	258.95	0.0239	IO to LS
B16	Push Y Min	-261.52	-0.0245	IO to LS
B17	Push Y Max	262.27	0.0255	IO to LS
B19	Push Y Max	259.08	0.0239	IO to LS
B19	Push Y Min	-262.09	-0.025	IO to LS
B20	Push Y Max	261.14	0.0246	IO to LS
B20	Push Y Min	-261.14	-0.023	IO to LS

Table 5.33: Beam rotations after rehabilitating IR8F-I Case 4– column is removed from the corner of the building. (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	429.38	0.0252	IO to LS	B15	Push Y Max	443.48	0.0334	IO to LS	B11	Push Y Max	446.17	0.0344	IO to LS
B11	Push Y Min	-423.67	-0.019	IO to LS	B15	Push Y Min	-438.24	-0.0292	IO to LS	B11	Push Y Min	-446.24	-0.0349	IO to LS
B15	Push Y Max	422.48	0.0217	IO to LS	B16	Push Y Max	246.94	0.0046	A to IO	B15	Push Y Max	445.07	0.0347	IO to LS
B15	Push Y Min	-430.63	-0.0239	IO to LS	B16	Push Y Min	-250.95	-0.0100	IO to LS	B15	Push Y Min	-445.68	-0.0348	IO to LS
B17	Push Y Max	31.01	0.0025	A to IO	B17	Push Y Max	242.85	0.0001	A to IO	B16	Push Y Max	249.26	0.0060	A to IO
B17	Push Y Min	-85.25	0.001	A to IO	B17	Push Y Min	-244.34	-0.0010	A to IO	B16	Push Y Min	-252.72	-0.0127	A to IO
B19	Push Y Max	83.55	0.0015	A to IO	B19	Push Y Max	242.35	0.0008	A to IO	B17	Push Y Max	246.68	0.0041	A to IO
B19	Push Y Min	-31.3	0.0010	A to IO	B19	Push Y Min	-242.85	-0.0008	A to IO	B17	Push Y Min	-246.25	-0.0046	A to IO
B20	Push Y Max	205.67	0.0210	A to IO	B20	Push Y Max	250.08	0.0088	A to IO	B19	Push Y Max	246.03	0.0045	A to IO
B20	Push Y Min	-192.6	0.0017	A to IO	B20	Push Y Min	-246.19	-0.0032	A to IO	B19	Push Y Min	-246.35	-0.0037	A to IO

Table 5.33: (continued) Beam rotations after rehabilitating IR8F-I Case 4– column is removed from the corner of the building (Story 5,4 and 3)

Story 5					Story 4					Story 3				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B16	Push Y Max	251.13	0.0119	IO to LS	B19	Push Y Max	251.32	0.0105	IO to LS	B15	Push Y Max	454.54	0.0399	IO to LS
B16	Push Y Min	-255.4	-0.0164	IO to LS	B19	Push Y Min	-250.19	-0.009	A to IO	B15	Push Y Min	-454.46	-0.0393	IO to LS
										B16	Push Y Max	259.78	0.0211	IO to LS
										B16	Push Y Min	-260.42	-0.0233	IO to LS
										B20	Push Y Max	260.33	0.0234	IO to LS

5.9 Rehabilitation of Irregular Buildings, (IR4F)

The failed beams are located and rehabilitation plans have been applied. The rehabilitation depends on replacing the removed column with a system of bracing members to resist the failure. Due to the mechanism behaviour of the bracing, the relocated bracings will transfer the loads coming from the upper beams to the lower column in the neighbouring bay.

5.9.1 Rehabilitation of IR4F Building with I-Beams Due to Pushover Analysis, (IR4F-I)

The failed beams are located and rehabilitation plans have been applied for Case2, Case3 and Case4.

Table 5.34: Beam rotations after rehabilitating IR4F-I Case 2 – column is removed from the long side (Gr1B) of the building.

Story 8

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B11	Push Y Max	437.08	0.0283	IO to LS
B11	Push Y Min	-425.92	-0.0212	IO to LS
B15	Push Y Max	427.32	0.0216	IO to LS
B15	Push Y Min	-429.75	-0.0261	IO to LS
B16	Push Y Max	251.11	0.0102	IO to LS
B16	Push Y Min	-259.58	-0.0217	IO to LS
B17	Push Y Max	31.612	0.0015	A to IO
B17	Push Y Min	-40.89	0.001	A to IO
B19	Push Y Max	44.014	0.0019	A to IO
B19	Push Y Min	-33.239	0.0013	A to IO
B20	Push Y Max	259.93	0.0228	IO to LS
B20	Push Y Min	-249.11	-0.0108	IO to LS

Story 7

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B19	Push Y Max	261.28	0.0824	IO to LS
B19	Push Y Min	-258.04	-0.0836	IO to LS
B20	Push Y Max	270.52	0.0393	IO to LS
B20	Push Y Min	-265.75	-0.0336	IO to LS

Story 6

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B20	Push Y Max	275.69	0.0437	IO to LS
B20	Push Y Min	-271.69	-0.0382	IO to LS

Story 5

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	273.99	0.0414	IO to LS
B16	Push Y Min	-279.23	-0.0486	IO to LS
B20	Push Y Max	277.76	0.0492	IO to LS
B20	Push Y Min	-272.49	-0.0421	IO to LS

Story 2

Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
B16	Push Y Max	282.17	0.0555	IO to LS
B16	Push Y Min	-282.36	-0.0559	IO to LS

Table 5.35: Beam rotations after rehabilitating IR4F-I Case 3 – column is removed from the long side (Gr1C) of the building.

Story 8					Story 5					Story 3				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	431.39	0.026	IO to LS	B11	Push Y Max	447.64	0.0364	IO to LS	B15	Push Y Max	453.85	0.0383	IO to LS
B11	Push Y Min	-425.66	-0.0204	IO to LS	B11	Push Y Min	-446.61	-0.0369	IO to LS	B15	Push Y Min	-452.39	-0.039	IO to LS
B15	Push Y Max	422.08	0.0205	IO to LS	B15	Push Y Max	446.93	0.0369	IO to LS	B16	Push Y Max	258.62	0.0208	IO to LS
B15	Push Y Min	-429.98	-0.0235	IO to LS	B15	Push Y Min	-449.16	-0.0365	IO to LS	B16	Push Y Min	-259.67	-0.0224	IO to LS
B16	Push Y Max	189.1	0.002	A to IO	B16	Push Y Max	249.16	0.0102	IO to LS	B17	Push Y Max	258.67	0.0215	IO to LS
B16	Push Y Min	-203.62	0.001	A to IO	B16	Push Y Min	-253.85	-0.0145	IO to LS	B17	Push Y Min	-256.46	-0.0202	IO to LS
B17	Push Y Max	32.1	0.0023	A to IO	B17	Push Y Max	247.41	0.007	A to IO	B19	Push Y Max	256.85	0.0201	IO to LS
B17	Push Y Min	-86.76	0.001	A to IO	B17	Push Y Min	-249.06	-0.0071	A to IO	B19	Push Y Min	-259.28	-0.0214	IO to LS
B19	Push Y Max	87.18	0.0024	A to IO	B19	Push Y Max	248.86	0.0074	A to IO	B20	Push Y Max	260.2	0.0224	IO to LS
B19	Push Y Min	-30.14	0.001	A to IO	B19	Push Y Min	-247.32	-0.0073	A to IO	B20	Push Y Min	-259.03	-0.0208	IO to LS
B20	Push Y Max	206.15	0.0015	A to IO	B20	Push Y Max	253.6	0.0145	IO to LS					
B20	Push Y Min	-191.38	0.001	A to IO	B20	Push Y Min	-248.94	-0.0102	IO to LS					
Story 7					**Story 6**					**Story 2**				
B20	Push Y Max	249.78	0.0084	A to IO	B20	Push Y Max	250.42	0.011	IO to LS	B16	Push Y Max	261.66	0.024	IO to LS
B20	Push Y Min	-245.91	-0.0031	A to IO	B20	Push Y Min	-246.46	-0.0066	A to IO	B16	Push Y Min	-259.83	-0.025	IO to LS

Table 5.36: Beam rotations after rehabilitating IR4F-I Case 4 – column is removed from the corner of the building. (Story 8, 7 and 6).

Story 8					Story 7					Story 6				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	429.5	0.026	IO to LS	B11	Push Y Max	441.58	0.0318	IO to LS	B15	Push Y Max	445.83	0.0342	IO to LS
B11	Push Y Min	-425.35	-0.0202	IO to LS	B11	Push Y Min	-443.78	-0.0329	IO to LS	B15	Push Y Min	-444.92	-0.0336	IO to LS
B15	Push Y Max	425.25	0.0202	IO to LS	B15	Push Y Max	440.47	0.033	IO to LS	B16	Push Y Max	247.89	0.0062	A to IO
B15	Push Y Min	-430	-0.0235	IO to LS	B15	Push Y Min	-436.93	-0.028	IO to LS	B16	Push Y Min	-249.44	-0.0109	IO to LS
B16	Push Y Max	190.43	0.0271	A to IO	B16	Push Y Max	245.78	0.0029	A to IO	B17	Push Y Max	245.89	0.0031	A to IO
B16	Push Y Min	-204.58	0.0021	A to IO	B16	Push Y Min	-249.63	-0.0081	A to IO	B17	Push Y Min	-246.15	-0.0034	A to IO
B17	Push Y Max	30.18	0.0026	A to IO	B17	Push Y Max	243.25	0.0017	A to IO	B19	Push Y Max	245.39	0.0036	A to IO
B17	Push Y Min	-87.7	0.0021	A to IO	B17	Push Y Min	-243.21	-0.0018	A to IO	B19	Push Y Min	-245.29	-0.0031	A to IO
B19	Push Y Max	86.29	0.0034	A to IO	B19	Push Y Max	241.28	0.003	A to IO	B20	Push Y Max	251.46	0.0107	IO to LS
B19	Push Y Min	-30.13	0.0023	A to IO	B19	Push Y Min	-241.55	-0.0022	A to IO	B20	Push Y Min	-248.16	-0.0062	A to IO
					B20	Push Y Max	247.29	0.0081	A to IO					
					B20	Push Y Min	-243.53	-0.0028	A to IO					

Table 5.36: (continued) Beam rotations after rehabilitating IR4F-I Case 4 – column is removed from the corner of the building (Story 5 and 3).

Story 5					Story 3				
Frame	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**	**Frame**	**Load Case**	**M3 kN-m**	**R3 Plastic rad**	**Hinge Status**
B11	Push Y Max	448.84	0.0364	IO to LS	B16	Push Y Max	258.85	0.0205	IO to LS
B11	Push Y Min	-445.7	-0.0368	IO to LS	B16	Push Y Min	-258.48	-0.0224	IO to LS
B15	Push Y Max	445.21	0.0364	IO to LS	B17	Push Y Max	259.46	0.0214	IO to LS
B15	Push Y Min	-444.94	-0.0366	IO to LS	B17	Push Y Min	-258.24	-0.0199	IO to LS
B16	Push Y Max	248.98	0.0099	A to IO	B20	Push Y Max	256.3	0.095	IO to LS
B16	Push Y Min	-254.03	-0.0142	IO to LS	B20	Push Y Max	254.2	0.0812	A to IO
B19	Push Y Max	248.84	0.0072	A to IO					
B19	Push Y Min	-247.36	-0.0072	A to IO					
B20	Push Y Max	253.89	0.0142	IO to LS					
B20	Push Y Min	-248.89	-0.0099	A to IO					

5.9.2 Rehabilitation of IR4F Building with Truss Beams Due to Pushover Analysis, (IR4F-T)

The failed beams are located and rehabilitation plans have been applied for Case3.

Table 5.37: Beam rotations after rehabilitating IR4F-T Case 3 – column is removed from the long side (Gr1C) of the building.

Story	Frame	Load Case	M3 kN-m	R3 Plastic rad	Hinge Status
Story8	B12	Push Y Max	123.36	0.0025	A to IO
Story8	B12	Push Y Min	-172.85	0.002	A to IO
Story8	B13	Push Y Max	285.61	0.0055	A to IO
Story8	B13	Push Y Min	-313.34	-0.0045	A to IO

When columns were removed from short and long sides and corner of the building the magnitude of beam rotations were higher for floors with I-beams when compared with floors with truss beams.

Chapter 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

6.1 Summary

This chapter summarizes the goal of this study. Furthermore, it also gives the main results from this research. There are numerous serious threats which could cause progressive collapse in a structure that may result in loss of lives. There has been numerous research carried out in this field over the past few decadeas. However, the PC of buildings in the past and the recent terrorist attacks that threaten buidling for PC, highlights the necessity of assessing progressive collapse.

This work was aimed to compare the vulnerability of an 8 story regular and irregular building by using linear and nonlinear static analysis. Furthermore, I-beams and truss beams were used as floor beams in this study in order to investigate and compare their effect when buildings are subjected to linear and nonlinear static progressive collapse analysis. Buildings PC performance due to sudden removal of a column was evaluated.

The demand capacity ratios (DCRs) for linear analysis and rotations for nonlinear analysis were considered for understanding the analysis results (GSA, 2003).

6.2 Conclusions

The following are the conclusions drawn from the analysis results of different buildings when column was removed from the short sides, long sides and corners:

1. After removing the columns using load combination of 2DL+0.5LL for LS analysis and DL+0.25LL for NLS analysis (GSA, 2003), the vertical displacement at the column removal location for floors with I-beams was greater than the floors with truss beams. In a similar study by S.Fadaei (2012), the LS analysis results showed that both the vertical displacements and the potential of PC of I-beams were more than the truss beams due to one column removal.

2. When columns were removed from short side, long side and corner of the building the magnitude of DCRs and rotations were higher for floors with I-beams when compared with floors with truss beams.

3. By comparing the results due to removing columns from the short, long and corner sides of the buildings the magnitudes of DCRs and rotations are suddenly decreasing for RB-I, IR8F-I and IR4F-I. On the other hand, the magnitudes of DCRs and rotations are not increasing for RB-T, IR8F-T and IR4F-T.

4. When column was removed from short side, long side and corner of the building the magnitude of DCRs and rotations were higher for RB, IR8F and IR4F buildings with I-beams when compared with RB, IR8F and IR4F buildings with truss beams.

5. When column was removed from short side, long side and corner of the building the magnitude of DCRs and rotations were higher for RB buildings with I-beams when compared with IR8F and IR4F buildings with I-beams.

6. When column was removed from short side, long sides and corner of the building the magnitude of DCRs and rotations were higher for RB buildings with truss beams when compared with IR8F and IR4F buildings with truss beams.

6.3 Recommendations for Further Investigations

According the results and conclusions of this study the following are suggested be considered for further investigation.

1. In this study, LS and NLS methods were used for assessing the PC potential of buildings. Therefore, LD and NLD analysis can be used in future compare the results with the results of this study.

2. Exterior and interior column be considered in this kind of research. Hence, future investigation could be performed on due to the removal of interior columns.

REFERENCES

ACI 318-08. (2008). Building code requirements for structural concrete and commentary. American Concrete Institute (ACI). Farmington Hills, MI.

ASCE 7-05. (2005). Minimum design loads for buildings and other structures. Report: ASCE/SEI 7-05. American Society of Civil Engineers (ASCE). Reston, VA.

Astaneh, A. (2003) Progressive Collapse Prevention In New and Existing Buildings. 9th Arab Structural Engineering Conference, Nov-Dec 2003, Abu Dhabi, UAE, 1001-1008.

Crawford, J. (2002). Retrofit Methods to Mitigate Progressive Collapse. Proceedings of The Multihazard Mitigation Council National Workshop on Prevention of Progressive Collapse, Chicago. IL, July 2002.

DoD. (2005). Design of buildings to resist progressive collapse. Unified Facilities Criteria (UFC) 4-023-03, Department of Defense (DoD).

Dusenberry, D., Cagley, J., Aquino, W. (2004). Case studies. Multihazard Mitigation Council national workshop on Best practices guidelines for the mitigation of progressive collapse of buildings. National Institute of Building SciencesETABS. Version 13.2.2, Computers and Structures, Inc., Berkeley

ETABS Version 13.2.2, Computers and Structures, Inc. Berkeley.

Eurocode 0-Basis of Structural Design. EN 1990-2002

Eurocode 1:Actions on Structures, EN 1991-2002- part1-1 General actions-Densities, self-weight, imposed loads for buildings.

Eurocode 3-Design of Steel Structures, EN 1990-2002- Part 1-1:General Rules and Rules for Buildings.

FEMA-277. (1997). The Oklahoma City Bombing: Improving building performance through multi-hazard mitigation, Report: FEMA 277. Federal Emergency Management Agency (FEMA). Washington, D.C.

FEMA-403. (2002). World Trade Center building performance study: Data collection, preliminary observations and recommendation. Report: FEMA 403. Federal Emergency Management Agency (FEMA). Washington, D.C.

FEMA-427. (2003). Primer for design of commercial buildings to mitigate terrorist attacks. Report: FEMA 427. Federal Emergency Management Agency (FEMA). Washington, D.C.

Griffiths, H., Pugsley, A., Saunders, O. (1968). Report of inquiry into the collapse of flatsat Ronan Point, Canning Town. Ministry of Housing and Local Government. Her Majesty's Stationary Office. London, United Kingdom. GSA. (2003). Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects. General Service Administration (GSA).Washington, D.C.

Herrle, K. & McKay, A. Development and Application of Progressive Collapse Design Criteria for The Federal Government (Accessed April, 2012).

Houghton, D. (2000) Steel Frame Connection Technology of The New Millenium: Satisfying Heightened Performance Expectations With Simplicity and Reliability at Low Cost, 12th World Conference on Earthquake Engineering.

Humay, F. K., Baldridge, S. M. & Ghosh, S. K. (2006). Prevention of progressive collapse in multistory concrete buildings. Structures and Codes Institute (SCI).

Irving, C. (1995). In Their Name. Random House, Inc. New York.

Kaewkulchai, G., Williamson, E. B. (2003). Dynamic behavior of planar frames during progressive collapse. In: Proceedings of 16th ASCE engineering mechanics conference, July 16-18, University of Washington, Seattle.

Marjanishvili, S. M. (2004). Progressive analysis procedure for progressive collapse. *Journal of Performance of Constructed Facilities. 18(2), 79-85.*

Nair R.S. (2004). “Progressive collapse basics,” Modern steel construction, 37-42. Nair, R.S. (2006). “Preventing Disproportionate Collapse,” *Journal of Performance of Constructed Facilities, Volume 20, Issue 4, 309-314.*

New York Times, September 12, 2001.

NIST. (2005). Federal building and fire investigation of the World Trade Center disaster. Final report of the National Construction Safety Team on the collapses of the World Trade Center tower. National Institute of Standards and Technology (NIST). NCSTAR 1. Gaithersburg, MD.

RLSD. (2012). Accessed on June 27, 2012 and downloaded a text form http://www.RLSD.com/downloads/RLSD_TM1.pdf

Ruth, P., Marchand, K., & Williamson, E. (2006) Static Equivalency in Progressive Collapse Alternate Path Analysis: Reducing Conservatism While Retaining Structural Integrity. *Journal of Performance of Constructed Facilities, 4(20), 349-364.*

Starossek, U. (2008) Avoiding Disproportionate Collapse of Tall Buildings. Structural Engineering International, March, 2008, 238-246.

Wikipedia. (2012). Accessed on June 09, 2012 and downloaded a picture from http://en.wikipedia.org/wiki/File:Ronan_Point_-_Daily_Telegraph.jpg

Wisegeek. (2012). Accessed on June 11, 2012 and downloaded a text from http://www.wisegeek.com/what-is-a-truss-beam.htm