Seismic strengthening of Reinforced Concrete Structures using External Lateral Post Tensioning

التقوية الزلزالية لهياكل الخرسانة المسلحة باستخدام الشد الجانبي الخارجي

by

USHA MURUGESAN

Dissertation submitted in fulfilment

of the requirements for the degree of

MSc STRUCTURAL ENGINEERING

at

The British University in Dubai

December 2020

DECLARATION

I warrant that the content of this research is the direct result of my own work and that any use made in it of published or unpublished copyright material falls within the limits permitted by international copyright conventions.

I understand that a copy of my research will be deposited in the University Library for permanent retention.

I hereby agree that the material mentioned above for which I am author and copyright holder may be copied and distributed by The British University in Dubai for the purposes of research, private study or education and that The British University in Dubai may recover from purchasers the costs incurred in such copying and distribution, where appropriate.

I understand that The British University in Dubai may make a digital copy available in the institutional repository.

I understand that I may apply to the University to retain the right to withhold or to restrict access to my thesis for a period which shall not normally exceed four calendar years from the congregation at which the degree is conferred, the length of the period to be specified in the application, together with the precise reasons for making that application.

____

Signature of the student

ABSTRACT

The constructions of buildings before the 1970s where not in coherence with the seismic design or any type of seismic codes hence the buildings have to be investigated and do the necessary strengthening to withstand the seismic effect. Those vulnerabilities of structures which has added forth and raised cognizance for seismic Strengthening needs. Design codes now consist of seismic provisions, and those buildings which are constructed in the future are earthquake-resistant structures. Surveys after earthquakes have been analysed to interpret the collapsed structures to study and learn the possible failure causes and mechanisms. The most destructive natural hazards is earthquake. A seismic event may cause a huge loss of property as well as life. It is estimated that around 10000 people are killed every year due to calamity. This, in turn, results in a huge annual economic loss. Hence the construction industry takes critical steps to prevent and avoid the collapse as well as reduce damages caused to the structures. The method of externally applied post tensioning of tendons (EPT) is a powerful method of strengthening and repair of structure which are in existence. The technique of EPT can be used in all types of framing i.e.; to concrete buildings, structural steel buildings and wood structures. It's a unique method of strengthening in which the strength of an existing structure is increased for its stability and also reduces the deflection in an existing structure which have been through an earthquake damage.

نبذة مختصرة

إنشاءات المباني قبل السبعينيات حيث لم تكن متسقة مع التصميم الزلزالي أو أي نوع من الرموز الزلزالية ومن ثم يجب فحص المباني والقيام بالتعزيز اللازم لتحمل التأثير الزلزالي. نقاط الضعف في الهياكل التي أضافت ورفع مستوى الإدراك لاحتياجات التعزيز الزلزالي. تتكون رموز التصميم الآن من أحكام خاصة بالزلازل ، والمباني التي يتم تشييدها في المستقبل هي هياكل مقاومة للزلازل. تم تحليل المسوحات بعد الزلازل لتفسير الهياكل المنهارة لدراسة ومعرفة أسباب الفشل المحتملة وآلياته. أكثر الأخطار الطبيعية تدميراً هو الزلزال. قد يتسبب الحدث الزلزالي في خسارة فادحة للممتلكات وكذلك الأرواح. تشير التقديرات إلى أن حوالي 10000 شخص يقتلون كل عام بسبب الكارثة. وهذا بدوره يؤدي إلى خسارة اقتصادية سنوية ضخمة. ومن ثم تتخذ صناعة البناء خطوات حاسمة لمنع وتجنب الانهيار وكذلك تقليل الأضرار EPT هي طريقة فعالة لتقوية وإصلاح الهيكل الموجود. يمكن استخدام تقنية (EPT) التي تلحق بالهياكل. طريقة شد الأوتار المطبق خارجيًا في جميع أنواع الإطارات مثل ؛ للمباني الخرسانية والمباني الفولاذية الهيكلية والهياكل الخشبية. إنها طريقة فريدة لتقوية حيث يتم زيادة قوة الهيكل الحالي من أجل ثباته ويقلل أيضًا من الانحراف في الهيكل الحالي الذي تعرض للضرر الناتج عن الزلزال.

DEDICATION

This Dissertation is dedicated to my parents

Murugesan P, B.E

and

Vanaja N, B.A

who have given me invaluable educational opportunities

and also, My brother and the Entire Program of Structural Engineering

for their endless support and encouragement

ACKNOWLEDGEMENT

Foremost, I would want to thank the Almighty to keep up my patience and motivation to achieve my goals and desires.

I would like to express my sincere gratitude to my advisor Dr. Abid Abu-Tair for the continuous support of my MSc study and research, for his patience, motivation, enthusiasm, and immense knowledge. Through this difficult time in the world, he has helped me to complete my dissertation at ease. I sincerely thank my fellow friends and colleagues for enlightening me with their intellect. Last but not the least, I would like to thank my parents for supporting me always throughout my life in all my happy and difficult times.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

SYMBOLS

R_d	is the Damage index
T_i	is the measure of the tensile force at i^{th} test
$T_{i,e}$	is the tension force estimated at the i^{th} test
γ	is the characterizes the structural behaviour of the tendon / cable
ℓ	is the cable length
f_1 and f_2	is the natural frequency in first mode and second mode respectively
T	is the lateral stiffness of tendon / cable depending on tensile force
h	is the derivative tension
EI	is the bending stiffness
m	is the mass per unit length
P	is the external point load
δ	is the Dirac delta
C	is the natural frequency from function of transcendent

CHAPTER 1: INTRODUCTION

1.1 Research Background:

A seismic event or in other words an earthquake can be interpreted as a motion of waves produced under the layer of earth's surface which propagates through the crust of the earth. These waves can also be elucidated as vibrations which rise to a dangerous level causing tremors to the surface of the earth as a result of dissipation of energy through the crust. However, to put it in general definition an earthquake is simply a motion of the surface in vertical and horizontal directions. The seismic event can be sudden which is a natural cause happening at or even below the earth's crust. A seismic event or an earthquake is one of the major drawbacks all over the world hence it is very critical problem which effects the structural integrity of any building severely which are built. Therefore, these seismic forces needed to be studied and engineer the building for strengthen and repair using various techniques. Hence when designing or constructing a building an approved building codes along with the seismic codes for structures has a very important integral part in making the respective building safe. However, due to some incapability or inadequacy these norms are not followed, therefore the building loose its strength after the first event of earthquake. So the need for strengthening the building becomes critical. To overcome such defects or repairs many methods of seismic strengthen have been implemented. Structural engineers strive to make these methods better through the vigorous analysis and investigations. One such efficient and economical method is External Post Tensioning method. It is a technique which can be installed with absolute ease compared to all other methods. It is applicable to all types of structural buildings such as RCC buildings, steel buildings as well as wood structures. Its individual approach of strengthening an existing structure to increase strength and reduce deflection makes it one of the most economically advantage methods.

1.2 Research Significance:

A seismic event is one of the most frequent critical calamities relative to most of the natural disasters encountered on earth due to its unpredictability. In other terms an earthquake id a sudden outburst of the accumulated energy in the crust of the earth thus resulting in a seismic wave. These waves will radiate an outward force from its focal source at variable speeds which leads to the shaking intensely of the surface of the earth. These surface shakes will affect the structural system of any building causing a severe or catastrophic damage as well as miseries to the people and the environment.

Thus, a building has to resist such a calamity to prevent losses. Hence to ensure the structure to be resistant as well as responsive to the seismic events a deep investigation and researches are carried out before the construction itself. However, this is also applicable to those structures which have been affected by earthquake and needs to strengthen. While these aspects are important the serviceability as well as the structural damage control and the prevention of building failure are to be considered while keeping the ultimate goal / objective to achieve a reduction in down time, repairing budget to be minimum and importantly the system implemented to defend life without compromising the performance boost design it would provide. Thus, there are many methods implemented for the seismic building strengthening to reach to this agenda. Strength, hyper-strength, damping, stiffness and the docility are yet another aspect in the hierarchical structure which paves way for the strategic method implemented. Hence External Post Tension method (EPT) is found to be more reliable as well as economical relative to other methods available in the constructional engineering field.

1.3 Research Objectives:

The work carried out in this research will focus on the seismic strengthen methods implemented over the decades to make the structural integrity to resist against an earthquake. It primarily focuses on the most anticipated and researched technique to strengthen the buildings which is External Post Tension method (EPT). Moreover, the research advances to state the constructional faults and steps by reiterating the inadequacies and incapability during the stage of design and construction of the building. The investigations and researches thus made will give a significant understanding of the seismic strengthen methods primarily External Post Tension method (EPT) as well as the constructional dilemma which is it improve in the future of structural buildings. The work intends that the reader's attention to purely focus on the seismic strengthening method which is External Post Tension method (EPT) has significant capability in withholding even a old structure to resist against an earthquake in contrast with the other methods introduced of strengthening.

1.4 Research Methodology:

The approach for the research is preferably affiliated to a distinct technique.

A general narrative is on critical problem encountered in structural buildings which is earthquake. The discussion is carried further with the brief explanations on the techniques and methods implemented over the decades to minimize the losses encountered during a seismic event. After which a prime focus is made on the most economical method of seismic strengthening which is External Post Tensioning (EPT) method on the basis of its workability, feasibility and advantages. A jest of the parameters applicable to the External Post Tensioning (EPT) to understand the importance of the steel tendons and other respective elements in the system used. Moreover, examples as well as a detailed case study is discussed to provide an in-depth view on the Seismic strengthening of the building using External Post Tensioning (EPT) method. The methods thus discussed herein are expected to narrow down to External Post Tensioning (EPT) technique as well as an efficient working method for constructional ethics and more importantly practicability worldwide.

1.5 Research Challenges:

The developments in the technology over decades have been significant and tremendous in the field of construction. Thus, many norms / codes, methods and safety measures are formed which are made to make the building safe considering loses of life as well as property. A brief discussion the following sections will enlighten why the seismic part in construction is very vital and not to be overlooked upon. Thus, the time required to achieve the work was a primary constraint to read and review which would be relevant to the recent times. The limited amount of literature available for researches or studies on the External Post Tensioning (EPT) method also made the work to be challenging. Hence this work is intended to enlighten all the readers to understand the seismic problems and the most economical method to encounter it with a quick explanation in upcoming chapters.

1.6 Organization of Dissertation:

The work carried out in this research intends to bring about the strengthening of the seismic effected structures using one of the most feasible and economical method which is the External Post Tensioning method. Moreover, the work discusses the critical parts of the seismic performances of a building, other methods of seismic strengthening as well as the problems and inadequacies found in the construction of a structure.

An appraisal of the limited available literature of the seismic performances problems as well as External Post Tensioning (EPT) Method has been carried out in Chapter 2 while focusing on EPT major design provisions.

However, Chapter 3 deals with a general problems and damages during construction along with the brief of several seismic strengthen conventional practiced in field of construction.

Chapter 4 is the segment where the review on External Post Tensioning Method have been expresses in brief with its general concept, pros and cons. Furthermore, with an overview of the technique

Chapter 5 is a section intends to brief about the External Post Tensioning Method though a case study.

The final chapter 6 depicts the conclusion of the research work summarizing the seismic performances along with the merits of External Post Tensioning Method

CHAPTER 2: LITERATURE ON GENERAL SEISMIC RETROFITTING AND EXTERNAL POST TENSIONING (EPT)

2.1 Seismic Strengthening [1]

2.1.1 Introduction:

There are many layers to earth which has various characteristics. The outermost layer of the earth is called the crust. The crust is approximately in the range of 35 and 70km in the case of a continent. Thickness ranges between 5 and 10km for the case of the ocean floor. However, the layer under the crust called the mantle is divided into 2 parts i.e., lower and outer mantle. 2900km is the approximated thickness of this particular layer. Plate tectonics caused in the crust is due to the convection current generated in the mantle. Now the innermost layer of the earth is called the core which is also divided into 2 parts which are the first part to be a fluid outer core and the second part as a solid inner core. It is approximated that the inner layer is about 1200km in thickness and the outer layer to have 2300km thickness. The following image shows the schematic representation of the earth.

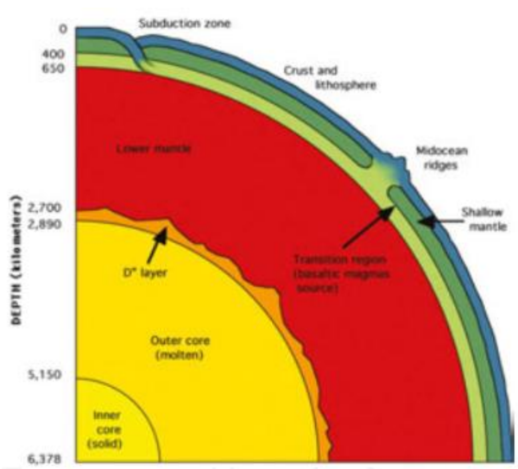

FIGURE 2.1: Schematic of Earth's Crust (Earthquake & Structural Damages)

The strain, as well as the movement of the crust, is dealt with by the plate tectonics. As per the Plate tectonic state of the art, when a seismic event is experienced by an area in the plate then the other areas also act relative as well to each other. These activities experienced by earth generates pressure shifts as well as the cooling stages in the layer of mantle results in the stresses in the crust. Thus, sliding is caused due to the increased stresses reaching to that of the bearing capacity of the crust fault. The starting point is the hypocentre causing the spread of the sliding movement to occur. Hence the accumulation of the strain energy thus discharges during sliding causing the seismic shaking.

Accumulation of elastic strain energy caused due to the movement of two plates over each other which is the result of a tectonic process. Hence the release of the two plates achieved through the interface zone's rupture. Immediate reactions from the shapeless blocks are shown at equilibrium. Thus, due to this activity a seismic motion is generated. Therefore, this cycle is known as the theory of elastic rebound. The fracture produced during the process in the earth's crust is known as a fault. The following figures are the simple illustrations of the mechanism of fault.

Seismic waves

Seismic waves are of two types which are generated during a seismic event which are surface waves and body waves. The waves which move through the earth's interior layers are called as the body waves. These waves are included in primary and secondary waves which are also known as P-waves and S-waves respectively. A sequential push and pull or compression and tension are generated by the Primary waves in the soil. The damage caused by these waves is very little. However, the Secondary waves move in a vertical-horizontal motion. Along the paths of their propagation, these waves generate shear stresses in the soil.

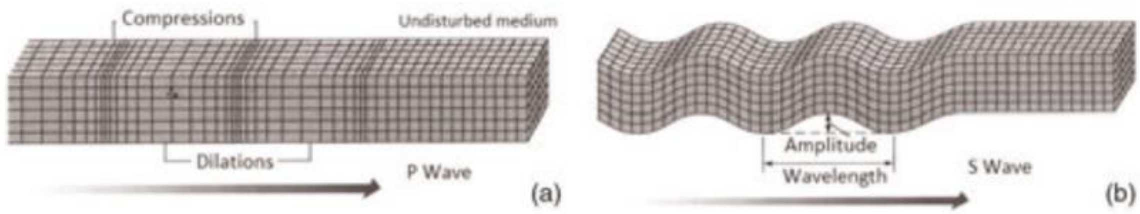

FIGURE 2.2: Representation of (a) Primary wave [P] & (b) Secondary wave [S] (Earthquake & Structural Damages)

<u>*Surface waves*</u>

Rayleigh (R) and Love (L) waves are the constituents of surface waves which travels through the layer in the outer part of the earth's crust. The body waves produce the waves which then propagate parallel to the surface of the ground and other underpass boundary layers. Due to displacement of these waves generated is large. At distance away from the source of the earthquake, the waves formed are of different types. During a shallow earthquake surface, waves can occur however body waves can occur in all depths. Due to the longer durations caused by the surface waves, it will affect the building severely. The following figures are the representation of the waves which have been discussed.

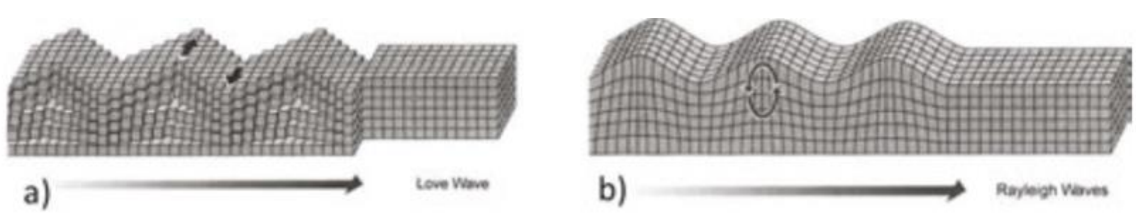

FIGURE 2.3: Representation of (a) Love wave [L] & (b) Rayleigh wave [R] (Earthquake & Structural Damages)

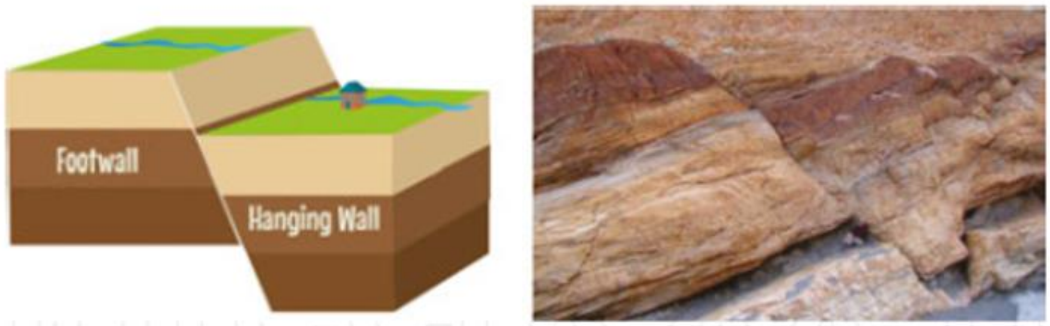

FIGURE 2.4: Mechanism and the graphical representation of Normal fault (Earthquake & Structural Damages)

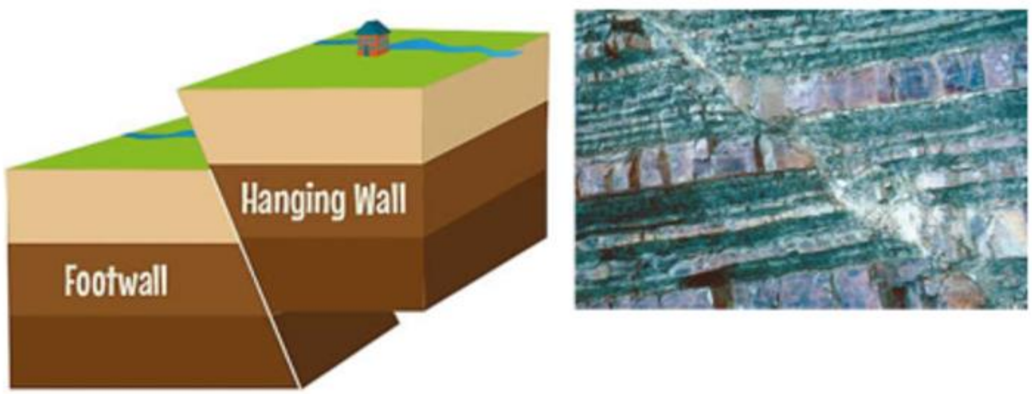

FIGURE 2.5: Mechanism and the graphical representation of Reserve fault (Earthquake & Structural Damages)

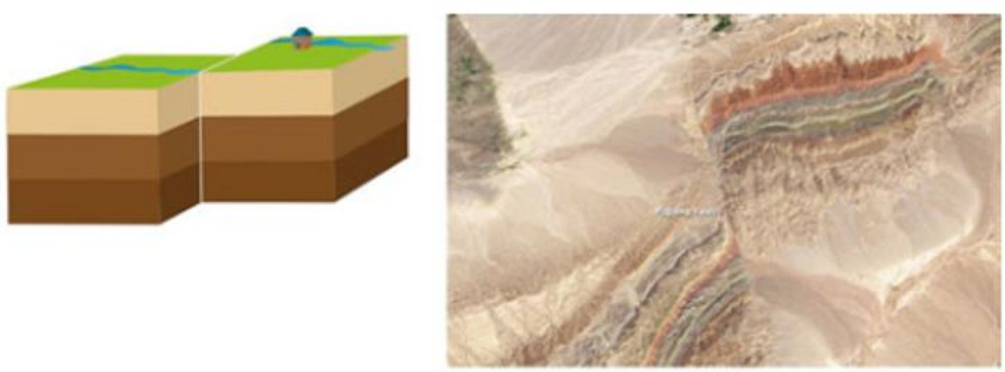

FIGURE 2.6: Mechanism and the graphical representation of Strip slip fault (Earthquake & Structural Damages)

Six distinct strategies of retrofit are segregated into the two major categories Local and global Strengthening methods. The primary is local methods that target the member. They include an evaluation of the shape to discover the elemental factors which are deficient and then retrofit the recognized ones. The types of Local retrofits are the addition of

a. Concrete
b. Steel
c. Composite Elements

These methods are intended to improve the efficiency of a specific member or element of its response during a seismic calamity. Even though all these three techniques are powerful enough they also have some disadvantages as well. These disadvantages can be summarized as follows

a. Need extensive labour for Concrete/RCC.
b. High maintenance is imminent during the life of the structure.
c. Composites assemblies have high preliminary cost

The Global method is the second type in the category that retrofits the complete structure to improve the building's overall capability and efficiency. This commendable method of Strengthening includes the addition of

a. Shear walls.
b. Metal bracings.
c. External placed tensioning.
d. Use of base isolation.

Just like the local method even the Global methods also have disadvantages which are

a. Labour and the construction of shear walls are intensive and overpriced.

b. Steel bracings erection seems to be easier however the connection of the joints will possess a real challenge.

c. An effective method is Base isolation and also works well, however, these are not suited or can be implemented for all types of structures.

The selection of the approach relies upon the construction, on its precise requirements, in addition to its locale, case, and geometry. Numerous methods ought to commonly be taken into consideration and as compared to find the appropriate good one. To offer greater flexibility in the retrofit system, numerous strategies can be combined for the best advantages of all the methods and then carried out together for better results.

2.1.2 Methods Leading to Seismic Damage [14]:

During an event of an earthquake, it causes catastrophic effects on the property as well as life. The potential of a seismic event being destructive can be of many factors such as the condition of the local site, focal depth as well as the epicentre distance However, the damages and the fatalities to a structure depend on the quality or lack of the engineering design, services, materials used moreover the workmanship. Thus, the following are some of the discussions done in various sector of the construction stage.

Response of reinforced concrete (R/C) structures

For example, in some RCC buildings at the ground level due to the reason for architectural, commercial, and functionality limitation the walls may have to avoid continuity along with height of the structure. Apart from this most of the time the below of the ground level are enclosed with windows made of glass instead of using brick infill walls. The above part of the ground level is constructed with partition walls for rooms for residential purposes. These are some of the reasons which can affect the end of a column by brittle failure. It is found that the soft-story mechanism is one of the most common modes of failure in a mid-rise RCC structure mostly in the first story. In any building, a weak story is made when failures tend to concentrate on a particular story if there is a sudden change in lateral strength in b/w of the stories adjacent. These sudden changes are due to the absence or lack of partition walls or this is due to the reason of insufficient column's cross-section. Hence these issue leads to the potential collapse partially or totally of a building during an earthquake. The following images are the representation of the damages.

FIGURE 2.7: Soft storey causing unexpected inter storey drift (Earthquake & Structural Damages)

Inadequate transverse reinforcement in columns and beams

At the time of a seismic event, there is an increase in shear forces at the beam-column joint as well as at the columns. Hence great attention and care has to spare to the design as well as a constructional aspect of the columns and the beam-column joint for the approach of performance-based design, the structures will have an increased ductility for the concern of seismic design. Most of the time there is a lack of transverse reinforcement in the area of the plastic hinge at columns of a structure. Due to which these structural elements will have low performances when experienced by dynamic loads. They lose their axial and shear load-carrying capacity. The following figure is the representation of this mode of failure.

FIGURE 2.8: A representation due to weak story mechanism (Earthquake & Structural Damages)

FIGURE 2.9: Inadequate spacing between shear reinforcement causing structural failure (Earthquake & Structural Damages)

Short column

Due to the adjustments done to the structural, maybe top continuous openings of infill walls which are in between the columns which helps the mechanisms of such type develops The columns and the shear walls will be the main element to take the lateral forces produced from an earthquake. These loads dissipation depends on the column's length which is a major aspect as well. The stiffness and the vulnerability to being brittle depend on the length of the column if the length decrease then it will be stiffer as well as more brittle in nature than the surrounding columns. Moreover, this insufficient length column tends to attract more shear forces. Due to which the shear failure occurs to such columns that are of concrete and hence the damages. The following figure is of a short column.

FIGURE 2.10: Representation of damages on short column (Earthquake & Structural Damages)

Inadequate gaps between adjacent buildings

Since there would be a lack of lots for the building in certain areas these structures tend to be constructed near to each other. One or two building's faces may be in contact. Therefore, during a seismic event, the lack of gap will start to pound each other. The pounding effect becomes very dangerous when the floors of the structure are not maintained at the same level. The following image shows the damage caused due to this lack of a gap between the buildings.

FIGURE 2.11: Adjacent building collapse (Earthquake & Structural Damages)

Strong beam–weak column

Sometimes for a flexibly designed column rigid and deep beams are used. Due to which the resistance towards the moment becomes more for the beam because of the dynamic loads than columns that are weak. Due to such approach shear failure, elastic behaviour or compression crushing leads to the plastic hinges over a column designed to flexible during a seismic event. The mode of strong beam weak column failure mechanism can be illustrated in the following image

FIGURE 2.12: Strong beam weak column effect causing structural failure (Earthquake & Structural Damages)

Failures of gable walls

Out of plane collapse is the most common mode of failure at the gable walls during an earthquake. Even though the gable walls are considered non-structural damages it may lead to loss of properties and lives. The damages over these walls can be due to reasons of lack of stability as well as the large lengths of walls which are not supported. The following is an image representation of such failures.

FIGURE 2.13: Gabble walls failure on the top of building (Earthquake & Structural Damages)

Poor concrete quality and corrosion

Lack of workmanship and the use of low strength concrete is yet another major reason for damages caused in a building. The most important factor to resist against an earthquake is the quality of concrete used for construction. Old buildings were generally constructed without the use of vibrators. So, the homogenous mixing was not available hence the required compressive strength was also lacking in these buildings. Moreover, the use of the corrosion-prone the Reinforcement bars, improper granulometric aggregates as well as utilizing a steel reinforcement which is smooth affects the concretes strength. These types of damages are shown in the following images.

FIGURE 2.14: Poor quality of concrete leading to structural failure (Earthquake & Structural Damages)

In-plane/out-of-plane effect

The combination of in and out of the plane wall movements is one of the major causes of the economic and life losses during an earthquake. The analysis of the in and out of plane interaction should be done properly since they are very complicated. Firstly, the ground story infills are expected to fail in a mid- and low-rise unreinforced infill RCC frames since they are prone to the highest in-plane demands. The bidirectional effects on which the ground motion has significantly two components will affect the infill walls of the upper the stories resulting it failing due to the combined effect of the in and out of the plane process. There is an increase of out of plane effects due to the acceleration increase. However, there is a decrease in the in-plane demand at the upper stories. To avoid this issue the capacity of the wall to carry the in-plane effect should be increased and the ductility of the out of a plane has to increase through applicable and possible development such as a wire mesh and a bed join reinforcement. The stiffness of a structural system can be increased by the applications to avoid detachment between the RCC elements and the infill wall. The following figure shows the in-plane and out of plane effects on a building.

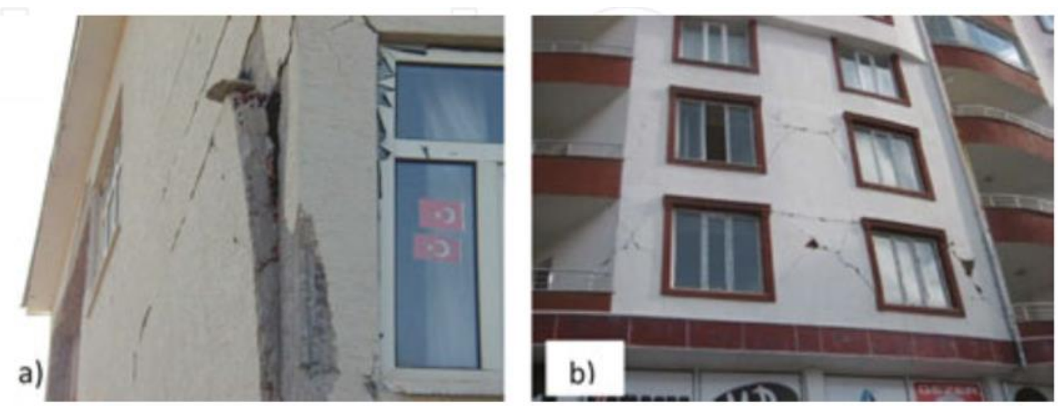

FIGURE 2.15: (a) Infill wall detachment during earthquake and (b) In-plane damage of during Earthquake (Earthquake & Structural Damages)

2.2 General narrative of the Literature on External Post Tensioning Method (EPT) [3&6]

2.2.1 General:

The External Post Tension (EPT) tendons were introduced as an alternate design instead of opting for Internal Post tensioning in buildings. These external tendons are located usually in the box girder made of concrete, which are then anchored using a deviator or in some case via diaphragms. This system has advantages which are discussed already when compared to the internal tendon configuration such as the inspection of the external system is much simpler due to the direct visual. Moreover, if the external tendon is found to be damaged or changed or replaced it can be achieved without significant effect on the structure. Due to these reasons the External Post Tension (EPT) system is considered durable and preferred.

The in-depth information on these external tendons is not widely available yet and researches as well as investigations have been carried out for decades. In the United States the technique of External Post Tensioning has been widely used to repair many structures which have been affected by a seismic event, notably after the Northridge earthquake in 1994 which is in the Southern California. The provision of external tendons was used for the seismic repairs which were almost identical to a gravity load repair.

The typical damages caused by an earthquake is that of a punching shear. Considering the case of Northridge earthquake event, the structure experienced a large vertical acceleration and it produced damages equivalent to a building with a two-way slab.

However, after researching and investigations into the case it was found that the punching shear capacity of the slabs did not satisfy the codes. Hence the use of external post tensioning was used to increase the strength of the punching shear section.

2.2.2 Review of Literature study on the use of External Post Tensioning Method [3]:

All the buildings are always subjected to beams which are cracked, those floor slabs which are sagging and spalled concrete. These problems which effect the building structurally can occur in the sections made of steel, Reinforced or prestressed Concretes (RCC) as well as wood made. These effects can be natural occurred due to seismic events or even manmade such as flaws in construction, errors during the design stage or it can be even to modify the building to increase the capacity.

Usual method of controlling or repairing such problems are adding steel beams underneath the sagging floor which would then need a supporting column as well at the structure's periphery or through the area of public use. These steel beams have to be designed for the full capacity to take the dead load and the live load which will have significant increase in the material quantities as well as the costs. Even though this technique will give the intended results it will have a negative impact over cost, time, and disruption of the building services. Some owners go up to demolishing the building as well and start from the planning stage.

Thus, to resolve all this hassle different types of methods are available for building repair as well as Strengthening. The usual method of post tensioning is the application of internally fixing in the reinforced concrete beams or the slabs using high strength cables or tendons which are completely covered during the time casting the concrete section. After the curing of the concrete is done a force of high tension is applied to those tendons. The tensile force thus generated from the tendon to the concrete member via the attached bearing plates. This process will enhance the concrete member to take more design loads without compromising the allowable tensile stress. However, in the Externally Post Tensioned (EPT) method, the tendons are placed outside the intended member to be strengthened like concrete, steel or even wood structure to enhance the strength.

Both the method of internal and external post tension uses the same steel tendon but in the case of fixing the internal post tensioning the walls or the columns are cores which can be a voiding damage to the rebar. However, in the case of the Externally Post Tension (EPT) method the steel tendons are placed under the intended member which requires strengthening (usually a floor slab). The saddles made of steel are placed at the pre-determined locations between the member and the steel tendon, after which these tendons are tensioned. Hence the tensioning will make the tendons to cause apply a vertical upward force at the intended member to strengthen thus achieving the desired results. One thing to be noted is to have precise control on the quality while implementing the Externally Post Tensioned (EPT) technique.

EPT Construction Sequence

The method of implementing the External Post Tensioning (EPT) for a floor slab is as follow

a. Holes are drilled to the existing columns members underneath the floor slab avoiding the rebar. These holes are drilled at considering the centre of the floor slab to fix the steel tubular sections for the method.
b. After the holes are drilled then the tubular steel sections are erected and bolted to the floor slab.
c. The tolerance gap maintained between the steel tube's bearing plate and the floor slab are dry-packed with non-shrink grout.
d. The steel tendons designed for the purpose is strung but tension forces are not applied yet.

e. Then these tendons are tensioned individually with the designed force one at a time. First in the east-west direction then in the north-south direction which will ensure the tension forces are equally applied to each bundle.
f. After the process the entire assembly is fire proofed by metal lath wrapping system and vermiculite plaster (by hand)
g. The residual gaps are closed / patched, the equipment's needed for the method is removed and the site is cleaned.

The example illustrates the fixing of a 15-floor condominium complex in L.A in United States (1980s). The building was built with a conventional reinforced concrete. At the stage of structural completion, the developer of the building went bankrupt and then it was taken over by new owner. This resulted in the modification of the building by adding more space. These changes affected the plumbing chases which was now unusable. To overcome this added problem almost 1000 holes which was up to 6 inches in the diameter to each story. This coring will affect the rebar system and it would be expensive to locate this rebar as well. The engineers in session assumed to need of 2000 bars and also determined that to restore the actual floor strength which was designed originally which is 44.5 kN of upward force needed to be focused at centre of each 270 floor bays. The usual method of steel beam column was impractical in this case and was not taken into consideration.

However, to apply 667 kN vertical load to the bottom of each steel tube column without extra support was almost impossible due to the false ceiling. This was overcome by placing system of EPT between the second-floor slab and first floor ceiling as shown in the image in the east – west sections. A provision of steel saddles at the lower end of the steel tube column using the pipe section welded to it as shown in the image. Each set of saddles and tendons are placed above as well as below.

The following image shows the forces in the downward on the short steel saddles are directed up. The structure is 3 bays wide hence there are 3 short saddle placed in the existing RC columns. A set of eight tendons are fixed to the either side of the column through a bearing plate as shown in the image. These steel tendons are then run under each provided saddles and the through the cored holes at the top of each column below the 2^{nd} floor.

These steel tendon bundles are tensioned up to the designed force of 111.2 kN per cable which will result in a residual of 13.4 kN upward force at the saddles each, 667 kN upward force at the bottom each as well. When the tendons are fully tensioned the External Post Tension (EPT) system will give a total upward force up to 2.7 million pounds to the intended floor slab of the building. The added advantage of this system is that it virtually does not add weight to the building.

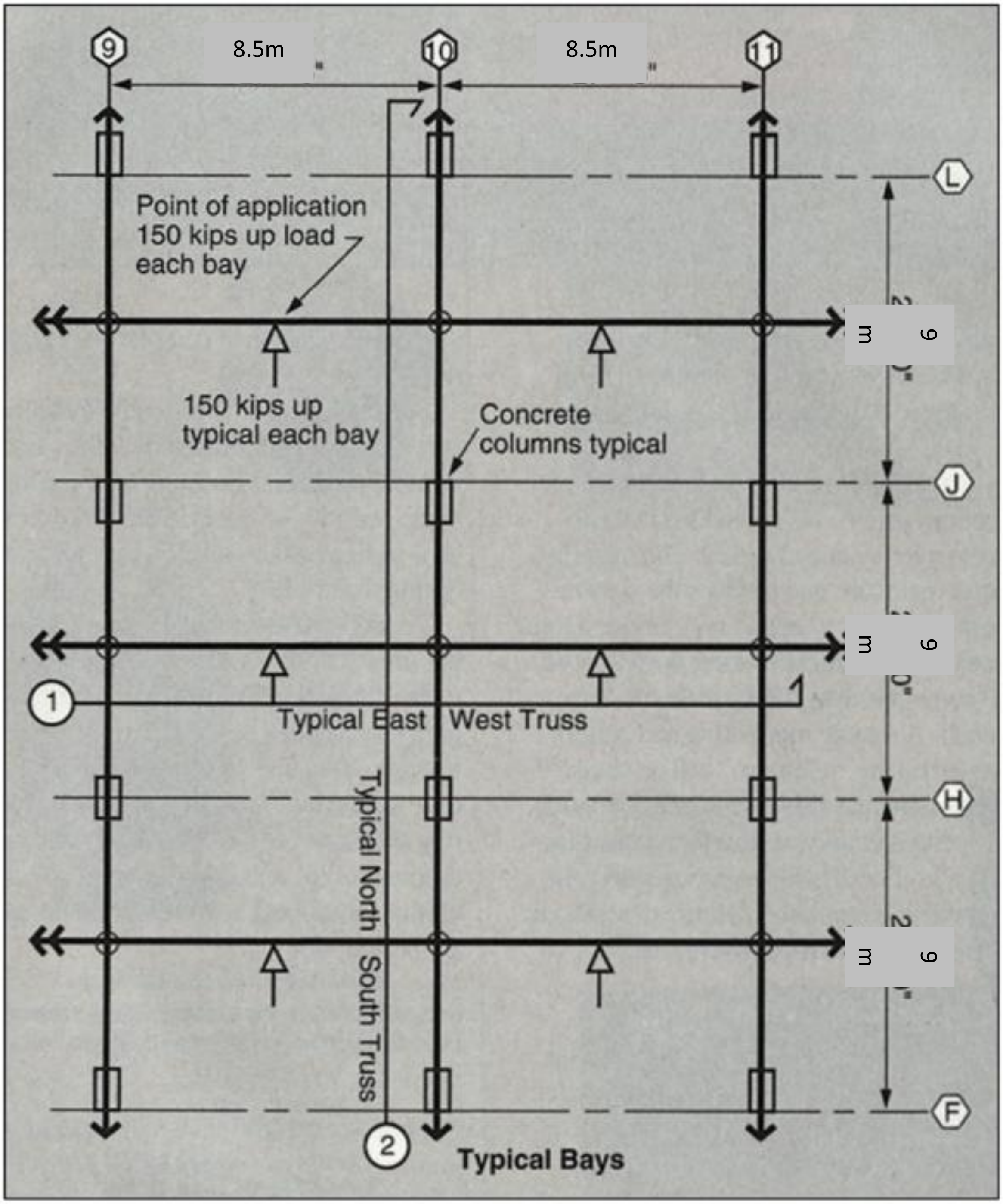

FIGURE 2.16: (a) Partial Floor plan: Circles are the representation of short saddles in between existing RC columns. Triangles indicates tubular columns in the centre of bays (Repair & Retrofit using External Post Tensioning)

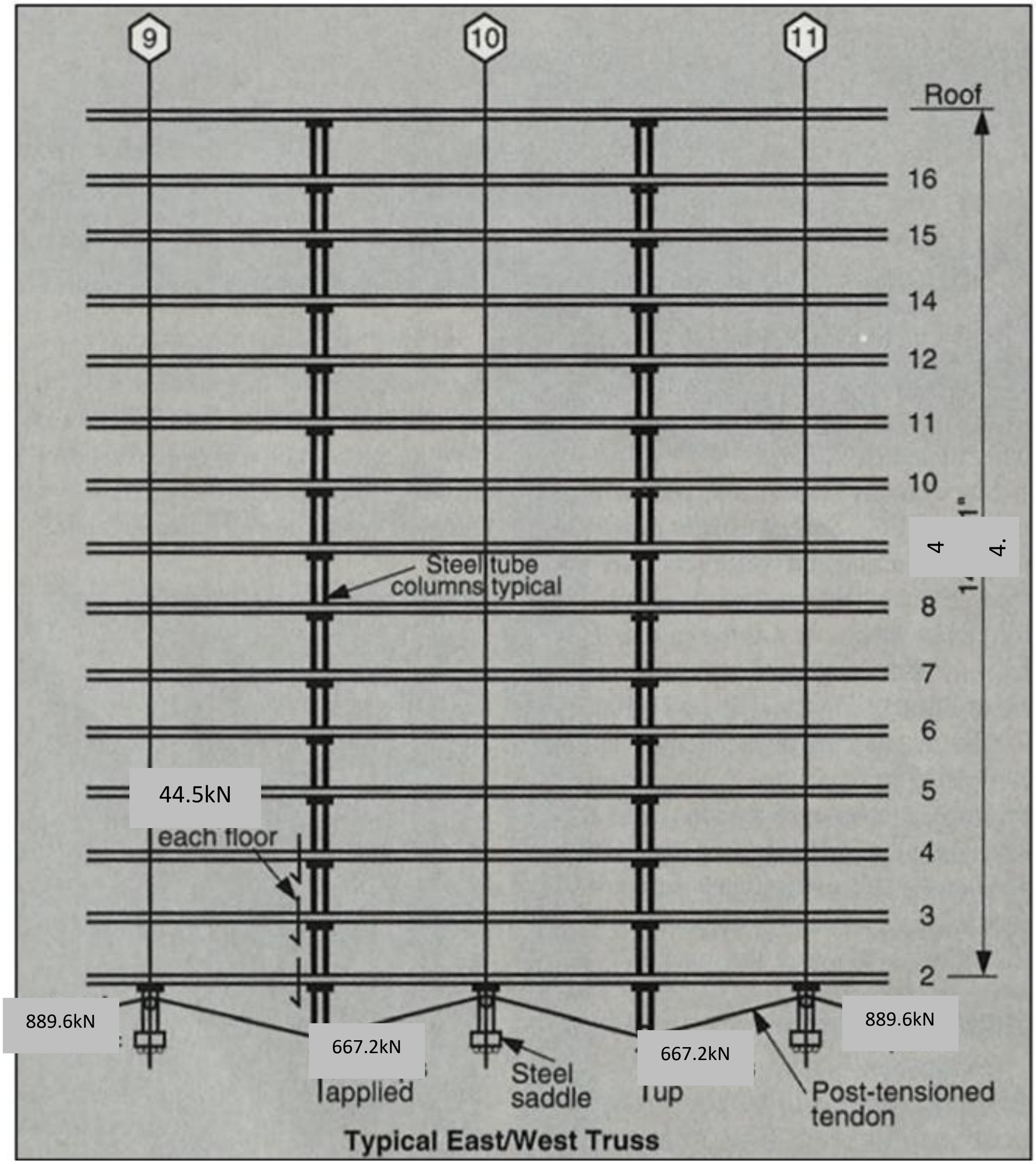

FIGURE 2.17: Section 1 of Figure 2.16, showing east/west truss. The system of post tensioning method is placed in between the second-floor slab and the first-floor false ceiling (Repair & Retrofit using External Post Tensioning)

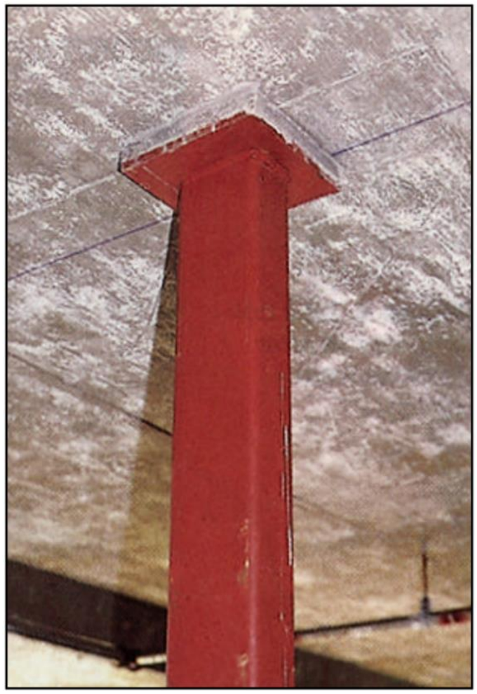

FIGURE 2.18: Typical arrangement of base plate for the steel tube section (Repair & Retrofit using External Post Tensioning)

FIGURE 2.19: Arrangements of column saddle after installation of steel tendon (Repair & Retrofit using External Post Tensioning)

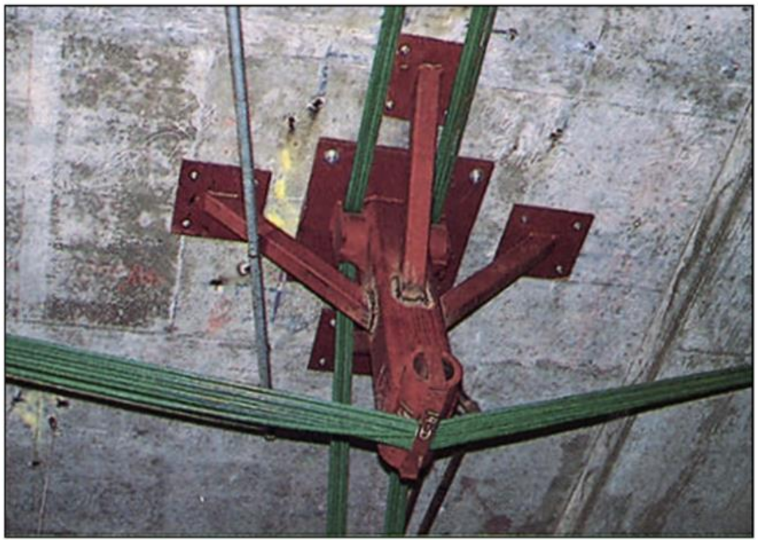

FIGURE 2.20: Arrangements of short saddle after installation of steel tendon (Repair & Retrofit using External Post Tensioning)

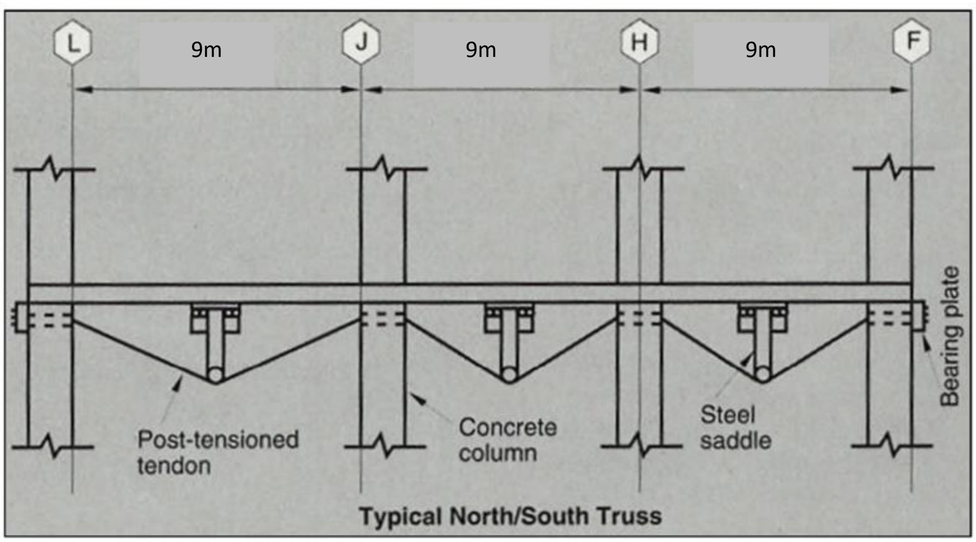

FIGURE 2.21: Section 2 of Figure 2.16, showing north/south truss. The post tensioning tendons taking the downward forces acted on the short steel saddles and transferring to the exiting RC columns (Repair & Retrofit using External Post Tensioning)

FIGURE 2.22: Typical Anchor plate bearing for the tendon (Repair & Retrofit using External Post Tensioning)

FIGURE 2.23: Representation of saddles and tendons pre fire proofing (Repair & Retrofit using External Post Tensioning)

It is almost impossible to find a corrosion damage in the prestressed steel by a regular inspection. Often these corrosion damages are realized when it has been severely progressed in which the buddle of tendons has been separated. This also can lead to the collapse without visual warning as well. The corrosion mechanism can be defined into two cases which are the stress corrosion / hydrogen embrittlement and high strength prestressing steel / stand exposed to the environment which is corrosive exhibiting an abrupt failure with no visual warning of corrosion product. Usually, the damage caused by corrosion is not uniformly distributed but it is localized to those areas of strands exposed to chemical or water. These may cause a sudden failure of tendon in the buddle as well as the damage on the grout caused by the tendon fracture will affect the structural response. Please see the image for more clarity.

The fractured strand which supported the tensile stress was redistributed to the other intact strands after the failure. Due to the failure the effectiveness of tensile stress redistribution is inconsistent. As per the degree of the damage as well as the redistribution of the stress extent of the causing damage was almost not critical i.e., the sensitivity of a localized damage when compared to the structural behaviour of the external post tensioning tendons decreases.

The strands in the buddle can be damaged of through accelerated galvanic corrosion, fatigue loading and direct exposure to chloride acid solutions. These will fracture the strands at severe damage level. These damages can take up to the 50% of the cross-sectional area of the tendons. The rate of damage can be found through the following

Damage index (R_d) =

$$R_D = \frac{\text{wires continuous along length of test specimen}}{\text{number of total wires}} \qquad (7)$$

It is very evident that the tensile forces generated in the post tension tendon is very important even though it is not measurable in the field. However, these forces can be measured in the form of vibrational signals. This is due to the fact that the vibrational behaviour is also tensile force governed. The method of measuring the vibration signal have been widely used in the application of stay cables to understand the structural integrity even though it is not widely used in the case of external post tension tendons especially when these strands are fractured / damaged. When the technique of the vibrational signal is used to estimate tensile force of the EPT tendon, the examined tensile forces from the tendon are compared to the measured tensile forces using tension ration (R_T) as per the following equation and residual tensile forces are measured using the approximate solution.

$$R_T = T_i/T_{i,e} \qquad (11)$$

Where T_i is the measure of the tensile force at i^{th} test and $T_{i,e}$ is the tension force estimated at the i^{th} test.

The approximation of the residual tensile forces from the EPT tendons are based on the natural frequencies which is not affected by the presence of corrosion or its extent of the damage. This scenario indicated that EPT tendon is indeed governed by the remaining tensile forces which is over a moderate to that of a severe level of the causing damage and that the grout damage do not affect the behaviour of the structure.

It is to be noted that the structural response did not decrease sensitively with that of a localized damage significant increased. Impeccably, the structural responses were affected after a certain degree of damage equivalently enough to cause fractures to the tendon bundle.

It is highly unlikely that a moderate level of damage is to be detected or even the integrity of the post tension tendon with damage through a common inspection technique like a visual observations or displacement/vibration measuring technique.

The corrosion damage is found only after it progresses significantly which leads to the fracture of the strands. This damage is inevitable and are not visually inspect able. Yet another damage at similar level can also be found in the EPT tendon. It is also a low sensitivity corrosion damage to that of the prestress forces. It is to be understood that the moderate corrosion damaged EPT tendon behaviour almost carries a similar behaviour to that of a non-damaged EPT tendon. Due to this fact the structure does not show any irregularities or excessive deflection or a visual product of corrosion.

Investigations & Researches based on EPT

As per the investigation carried out by University of Texas at Austin on the structural behaviour of Post Tension Tendons. It was conducted with a large-scale external Post Tension tendon where in the behaviour was more sensitive to the tensile stress compared to the internal post tensioned tendons.

a. The investigation of the structural effect due to the damages caused in EPT tendons where due to the 3 controlled methods fatigue loading, accelerated galvanic corrosion and direct exposure to chloride acid solution
b. These were monitored on the basis of visual inspection, transverse displacement, acoustic sensors, and vibration signals.
c. Those fractures tendons were governed by residual tensile forces continuously, which was then redistributed in the strands during when the damage caused was moderate.

Whish resulted in structural response to become larger when the level of damage was increased. It is to be noted that the damage did not influence the level of sensitivity.

d. The information thus arrived from the investigation apart from the importance or corrosion affecting the Post Tension Building is not totally correlated to the structural aspect of the building. Till date the effects structurally caused due to different levels of corrosion is not investigated experimentally, hence only minimal researches and studied have proposed analytical model to understand the deterioration degree of Post Tension structures. Thus, the analytical models determined the post behaviour of internal Post tension structure just after failure of the all the tendon which are post tensioned and focused due primarily on the estimation of residual tension after the re anchoring of those fractured tendons in the system. However, the critical parameter of the system is the bonding strength of the tendon bundle and the concrete involved.

As there was an increase level of localized damage the structural responses based on the natural frequencies, tensile forces and the transverse stiffness decreased. The reductions shown were not substantial when compared to the damage degree. Especially when the level of the damage caused is moderate, the sensitivity of the structural responses is not influenced by the damages. Hence the structural responses of low sensitivity to that of the localized damage increasing levels indicates that the tensile force was indeed redistributed to adjacent tendons from the fractured tendon.

During the damage caused post tension tendon the tensile force is considered to be the critical parameter. The residual tensile force generated governs the structural behaviour of the external post tensioned tendons regardless of the degree of the damage caused. This shows that the tensile force is only reasonably related to the damage applied. Based on the corresponding Natural frequency and transverse stiffness estimation of damage can understood as well.

There is no consistency of the level of damage caused compared to the residual forces. The residual tensile forces increased with the increase in the initial tension level and the damage accumulated also increased.

2.2.3 General Parametric Aspect [6]:

The approach of the external post tensioned tendon can be made as a cable member where it is governed by the tensile forces. The differential equations governing the deflection as well as the vibrations of the tendon / cable are in the following equations 1 and 2. The lateral stiffness of tendon / cable depends on tensile force (T), the derivative tension (h), the bending stiffness (EI) and mass (m) where P is external point load. Moreover, δ is the Dirac delta.

$$EI\frac{\partial^4 v(x,t)}{\partial x^4} - T\frac{\partial^2 v(x,t)}{\partial x^2} - h(x)\frac{\partial^2 v(x,t)}{\partial x^2} = P\cdot\delta(x - x_p) \quad (1)$$

Usually, the parameter of γ characterizes the structural behaviour of the tendon / cable. The tendons generally have a cross sections which is slender and it is long by which due to self-weight it will start deflecting thus affecting the structural behaviour. This cause is known as the geometric nonlinearity. Relative to that of the external post tension tendons which is usually subjected to tensile force which is in higher level and it is short, hence the geometric nonlinearity can be omitted. The cable length in the following equation is depicted as ‘ℓ’.

$$\gamma = (T\ell^2/EI)^{1/2} \qquad (3)$$

Typically, the natural frequency governs the structural behaviour of tendons / cables, rather than a transverse stiffness. This is due to the fact of related difficulties in getting a correct measurement as well as the calculations / computations. Many approximate solutions to understand the natural frequency from function of transcendent have been proposed. The following is the solution represented by the Zui et al. In the equation m is mass per unit length, f_1 and f_2 is natural frequency in first mode and second mode respectively.

$$C = \sqrt{EI/m\ell^4} \tag{4}$$

$$T = 4m(f_1\ell)^2[1 - 2.20C/f_1 - 0.550(C/f_1)^2] \quad (17 \leq \gamma) \tag{5}$$

$$T = m(f_2\ell)^2[1.03 - 6.33C/f_2 - 1.58(C/f_2)^2] \quad (17 \leq \gamma \leq 60) \tag{6}$$

CHAPTER 3: GENERAL PROBLEMS IN SEISMIC PERFORMANCES

3.1 General [11]:

Columns and piers

A number of buildings were found to have structural elements to be damaged in the seismic event. These structural damages or failures are often the cause of the collapse of a building. Few of the predominant defects for the structural elements such as columns/piers are the following

a) *The flexural strength was poor*: Generally, those structures before 1971 had lateral force coefficients ten percent less than the resulting demand of the structure's high potential ductility.

b) *Flexural ductility was insufficient*: Failure of such types are progressed from improper confinement or a lack of it at the core of the concrete which will be then preceded by the plastic hinge failure area. The kind of defects mentioned are flows in the structural design which are major. These are also a required pre-1971 practices, for the transverse reinforcements to the building's structural columns, Number 4 bars to be spaced at 0. 3m in the centre These were incorporated into all the columns without considering the shape/geometry or even measurements Moreover the usual methods were to use the transverse reinforcements to shut by the use of lap-splice Such strategies derived was not adequate enough to give an efficient anchoring to the rebar's when subjected to the pressure which resulted in the deformation of the bars and causes it to open. Hence methods have been found to efficiently shut the rebar which are anchoring it by bending towards the concrete core or by welding technique. These spalling of the concrete cover starts due to the limitation caused due to the inadequacies for the ultimate curvature at the column's area of plastic hinge which is 0.5%. Longitudinal strain is subjectively increased then the steel-hoops will untie which allow the confinement to be significantly lower.

c) *Flexural capacity was not reliable*: The design of longitudinal lap splices is to capacitate the compression which are usually to place near at the column's end. When the time of an earthquakes, high tension is experienced by the longitudinal bars in which those areas, where the plastic hinges may develop, are the areas where the splices must have been placed. The recent techniques and methods practices to place the splice at the centre of the structural column, moreover, these splices are designed to be as a tension element. The lap splices were traditionally having a length of 20mm dia. bar which were not enough to give the required yield strength (especially when wider diameter bars are chosen). These members will cause and adverse effect of reducing the flexural strength in the event of cyclic loading.

d) *Improper shear strength*: These types of failure mechanism often develop in those columns with a lower height to depth ratio, these can be due to the fact that these elements were initially designed to be short otherwise by using those elements which are not structurally considered to confine partially of the longer columns portion of its height which are also called as captive columns. The method used for structural design before 1971 are elastic method based in which the requirements s of the shear was considerably less Due to this, the column's shear strength is often deficient than the required for it to develop the members' flexural strength Failure due to shear are of brittle in an average which shows itself in the form a diagonal crack along with the full column length where the longitudinal reinforcements are also subjected to yielding.

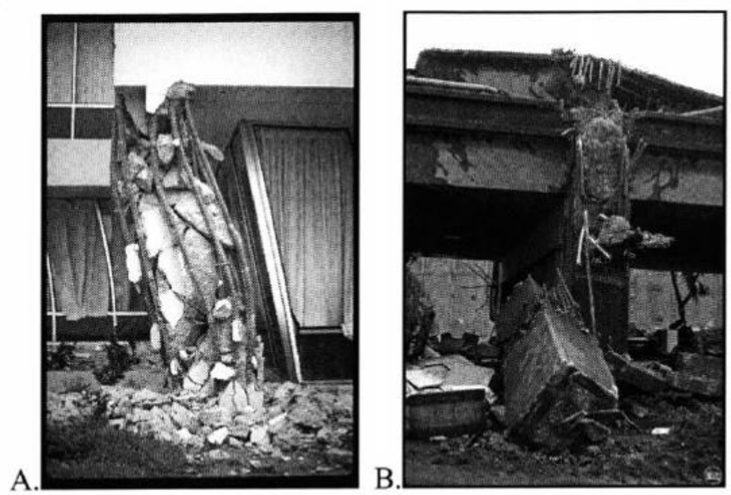

FIGURE 3.1: Representation of piers and columns collapse (Techniques of Seismic Strengthen for concrete structures)

There are few elemental factors which are relied upon to be the cause of the different modes of failure which are the geometrical aspects of cross-section, the columns height, reinforcements (both longitudinal and transverse) distribution as well as the potentiality of those elements which are considered stiffening.

Reinforced concrete frame

Framed structures are being practiced in seismic region with low to moderate risks Most of the times the lateral loads are not taken into account while considering only gravity loads the following are the problems created with the several deficiencies

Possibility of the Column not stronger than the connecting beam (weak column/strong beam behaviour). This may lead to the structural column sideways mechanism or a potential soft-story failure. Deficiencies in columns are almost the same as the aforementioned. It is often noted that a beam-column connection to be deficient Most of the time transverse shear reinforcement is not found and there is a discontinuation of bottom beam reinforcement inside the joints.

However, a lateral strength in a frame of gravity design will be of low resistance in turn, this will cause deformation on a large scale as well as causing large drifts within the story at the time of a moderate seismic situation Whereas at the time of a large earthquake the building will experience column sideways mechanism or a weak soft story due to the fact of improper or insufficient column ductility.

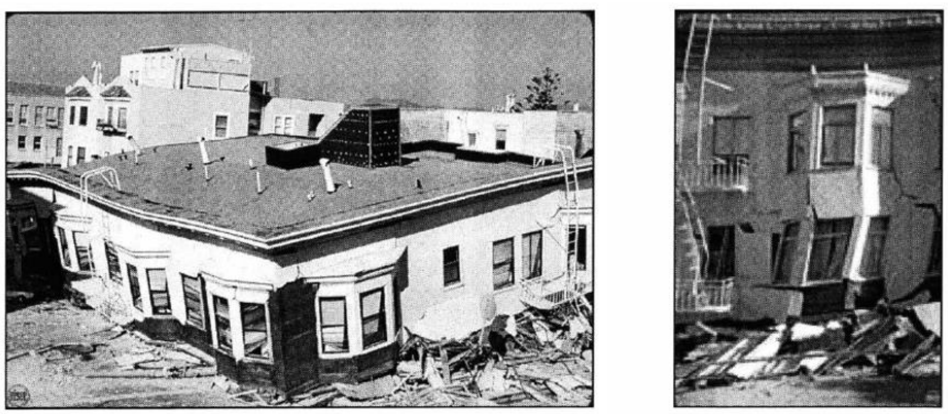

FIGURE 3.2: Representation of soft story collapse (Techniques of Seismic Strengthen for concrete structures)

<u>Other structural elements</u>

During an earthquake, it is found that other structural elements are also prone to failure effect. Few elements in this category would be a shear wall, coupling beams, and footings which may also experience this deficiency. It is interesting to know that the failure of such elements does not pose any threat to a sudden collapse of the whole building.

a) Failure of the footing: All the older footing were often capacitated and designed to take the gravity loads Due to which deficiencies can be expected on a large scale. First and foremost, these are recurring vulnerable and undersized to overturning moments. Secondly, the top reinforcement is not provided making the possibility of brittle failures Thirdly, these are often subjected to shear in footing column joint as well as the footing Lastly, the designs of the pile footing in buildings are found in deficient of structural connection between the pile cap as well as the piles

b) Shear walls and the coupling beams: It is often found that the shear walls are often subjected to damage as well as showing an X type cracks. Inadequate capacity of the coupling beams which can be specifically the shear capacity which are often less to develop the needed flexural yielding in the beam

3.2 Problems and Damages during Construction [12]

The performance of types of buildings constructions which withstood the seismic forces becomes evident after an event of an earthquake. An in-depth study into the buildings affected by the earthquake which have collapsed and the RCC have been broken will give a good as well as efficient insight to a possible engineering, architectural design failures. Moreover, it also provides with the other reasons which may have led to the failure such as the detailing mistakes, inadequate inspection and respective rectification on-site or construction mismanagement from the side of the contractors constructing the building. Usually, it is noted that the RCC building failures may be caused of the reasons such as the improper design of the columns and the structures those are overweight. These may lead to a fatal failure such as the collapse of the structures and loss of lives. For a RCC buildings use of stiff as well as heavy floor are untuneful to its total ductility and strength. The other problems include a sudden thermal expansion and the lack of proper execution skills.

Lately so many seismic events have shown that how hostile the structures can be. The catastrophe caused are severe during the earthquake hence to overcome it major events are charted, surveyed as well as evaluated to apprehend the reasons of the failure in the desire of understanding how to make a building to the withstand and avoid collapse in the future events during an earthquake. The building design are to be strictly apprehend the United Building Code or UBC. Hence as per the code, use of ductile detailing are to be considered important in the earthquake design. However, buildings nowadays have a better earthquake resistant design since the approach have had subsequent adjustments. Those structures which have been strengthened and went through earthquake events in which they suffered best constrained damages showing a positive result over the methods of Strengthening. The infamous California's bridges are such structures to be quoted as an example. After the Northridge earthquake IN 1994, the catastrophe caused in the 7 major freeways in and out of L.A. was severe. The California's department of transportation also known as CALTRAN had already strengthened around 122 bridges which were in L.A. withstood the seismic event without major damages. Those bridges which had been damaged during the earthquake was the ones to be strengthened in the list. However, it was revealed that if they have been strengthened before the seismic event the structures would have survived.

Failure to follow building design codes:

The performance of the structural design of a building becomes evident only after a seismic event whether it was carried out properly. However, the criteria of structural design are not same for all the types of the building. This becomes a concern if no National Code exits which would specify minimum strength.

The seismic or earthquake resistant code for structural design of a building depends on the country and the Zones of the seismic activity are contemplated and recorded as per the latest knowledge as well as the past/history. There are many nations where the buildings have been constructed as per the older version of the seismic building code. Usually, a restoration is planned for these older structures due to the impact of high cost. So, this helps the older building which have been restored as per the seismic code and its given zoning for its construction as well as the design to resist against in an event of an earthquake.

It was recorded that the earthquake in Haiti of 12th of January 2010 had a 7 Richter scale in magnitude It was a catastrophically damage with causalities about 230000. The earthquake had a shallow depth of 13km under the city. Yet another massive seismic event happened in Chile with a Richter scale reading of 8.8 in magnitude on the 27th of February 2010

Thus, these two events are studied and compared for the insight to construction and designing of building using the seismic building code.

Haiti, 12 January 2010	*Chile, 27 February 2010*
Earthquake with a Richter of 7 magnitude.	Earthquake with a Richter of 8.8 magnitude.
Shallow depth up to 13km	Moderate depth up to 35km
Peak Ground Acceleration (PGA) of 0.44	Peak Ground Acceleration (PGA) of 0.65
1.2 million Homeless and 222000 loss of life estimated.	2.1 million Homeless and 500 loss of life estimated.
The quality of the structures was poor. No Seismic Code where followed.	The quality of the structures where better. Most of the structures followed the recent Seismic Code.
Seismic codes are non-existent. No constructional control implemented by the government.	Seismic codes exist are used. Constructional control implemented by the government along with training the skilled labours.
History of earthquakes are not recorded hence lack of information to design a better structure.	Documentation of earthquakes are available.
Many buildings are constructed without engineers as well as the architects	The buildings are constructed with the engineers as well as the architects trained to have knowledge of the latest Seismic codes and designs.

TABLE 3.1: Comparison of seismic events

Since the construction of the buildings where better in Chile most of its buildings resisted during the seismic event even though the earthquake was stronger than the one happened in Haiti. This was purely due to the adherence of Earthquake resistant codes for buildings. Moreover, it also prevented many causalities unlike Haiti. This proves that control over construction and the training the architects as well as the engineers plays a major role in bringing up a performance of a building being build.

The main agenda of a building is to carry its self-weight as well as the occupants in it as live loads. The vertical load caused which is due to its self-weight is usually the major determining design factor. Most buildings easily withstand the tremor in the vertical direction which is also known as Rayleigh movement ‘P’. However, the structures build away from the epicentre often experience an increased type of rocking lateral force thus making the building to move backwards as well as forwards which will lead to major damages. The Peak Ground Acceleration (PGA) decides the amount of horizontal forces due to earthquake which would affect the structures foundations. The PGA varies as per the location or the soil structures of the building’s construction.

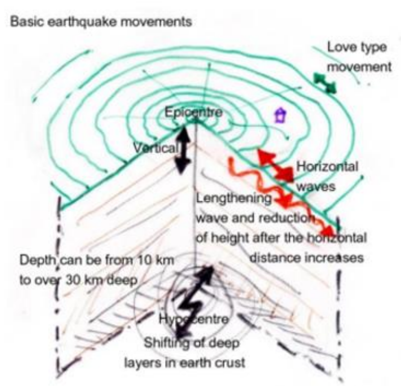

FIGURE 3.3: Schematics of Vertical and horizontal movement of seismic waves (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

A combination of waves from an earthquake affects the buildings as shown from the subsequent picture. The backward and forward movements the caused by the horizontal components of the wave length which is one of the Rayleigh type waves will have an increased time interval proportional to the measure of distance from that of the Epicentre. As the distance increases from that of the epicentre which will result in the diminishing of the amplitude of the waves.

The seismic code for the buildings is prepared on the basis to establish the balance between that of a seismic event risk happening in a given area as well as the impact of the economic cost of achieving a damage resistant construction. These codes guide to build by recommending the minimum criteria so as to prevent the collapse of a structure totally as well as to help tp avoid loss of life even if the construction may be economically in loss. To build a structure to withstand a Richter scale 8 earthquake a solution of concrete and brick may work but it would be very costly. However, an alternate to this problem would be using a ductile and lightweight design approach or utilizing the base isolation technique. The method of base isolation works well against the earthquake for tall buildings but for a wide and low structures it proves to be expensive due to the presence of double foundation structure.

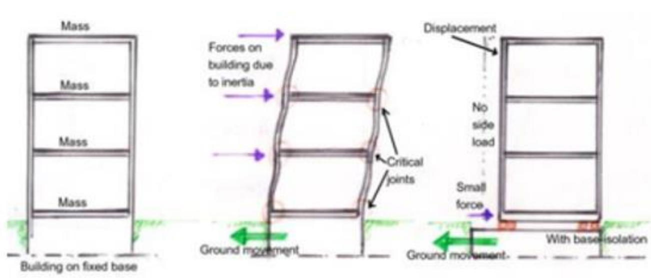

FIGURE 3.4: Representation of base isolation effect (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The technique of using base isolation for buildings can have flexible rubber or rollers as supports as well as combinations. A very small magnitude of horizontal loads is experienced at the top of the building foundation from the horizontal movement at the ground, which then results in the structure almost standing still on a fast base foundation movement. Due to the development of only forces which are small, the strength of the building can be worked out to economize when compared to the design in the left from the picture above. However, the cost of foundations is expensive. This is substantially a common technique followed in the construction of tall buildings. Moreover, the constructing a base isolation for an existing building would be difficult as well as expensive.

FIGURE 3.5: Structural failure before collapse (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

It is found that the top and the bottom of a ground level columns experience moment forces to be maximum making these areas to be the weakest in construction. Moreover, the quality of the concrete used is too low as well as there were no confinements where integrated to the columns in the areas of maximum moment force.

FIGURE 3.6: Structural failure due to lack of confinement (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The interaction between the concrete and the steel depends on the strength of reinforcement of the concrete where compression resistance from the concrete and the tension resistance from the steel will be worked. If the quality of the concrete used is compromised or forces exceedingly as per the design is experienced then the concrete crumbles and falls away from steel putting a stop to the interaction. Hence this will cause the steel to buckle resulting in the eventual collapse of the building. This is the most common mistakes encountered in the construction of the building in rural as well as the urban structures. Moreover, inadequate stirrups design in the areas of the maximum moment is also another example of a common mistake found.

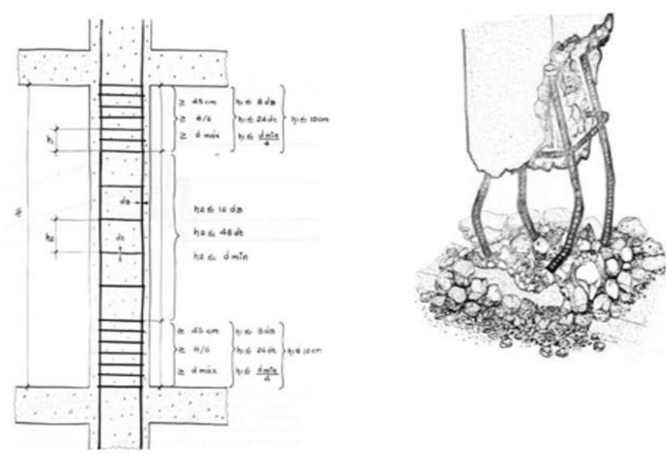

FIGURE 3.7: Confinement in the areas of maximum moment (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

Due to the earthquake, it causes the building to move horizontally. During the seismic event if the forces from the earthquake exceeds the actual compressive strength of the structures concrete, then the steel of on side of the building is stretched while compressing the concrete on the other side resulting in the breakage of the concrete. Due to this recurring movements as well as the inadequate stirrups the concrete which broke will eventually fall of and the bending of steel will occur proving to be useless then after.

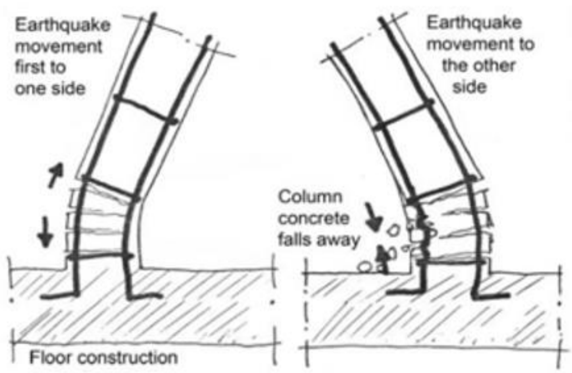

FIGURE 3.8: Crumbling Process (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The inadequate anchorages between the column as well as the supporting beam results in the disjoint of the beam and the column. The chances of this mistake may be possible due to the unspecified anchorage for the reinforcements in the drawing of the design. There also chances that the contractor did not follow the drawing provided.

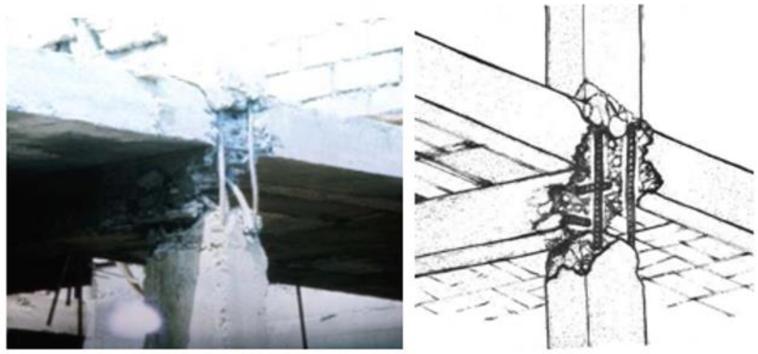

FIGURE 3.9: Improper detailing leading to no anchorage (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

These details are very important which it indicates the design control and the verification of the reinforcements done before the casting of the concrete. The reinforcement bars which are profiled gives an adherence as well as the anchorage better than the ones which are smooth typical steel bars. However, due to the higher strength given by these profiled steel bars the designed dimensions are smaller. The concrete may lose the adherence and crumble of the it is not of a correct strength. Providing hooks will give an extra length as well as the pull-out security.

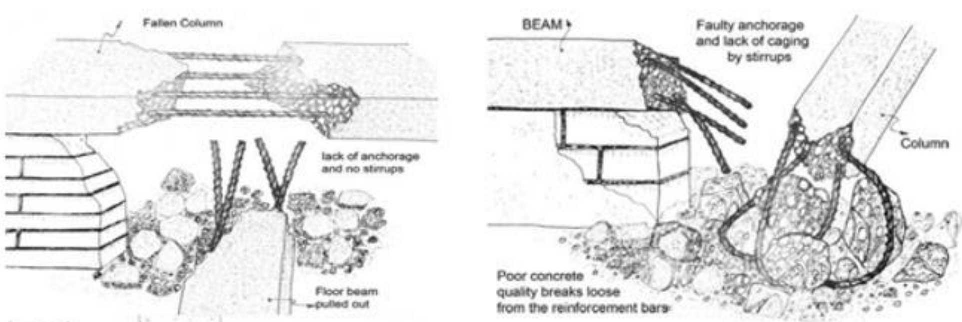

FIGURE 3.10: Improper detailing leading to lack of anchorage (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

As per the general RC Codes the minimum bar anchoring length linking beams to column to be maintained is 30cm. The seismic code is yet another part of the General Building code. Hence the specifications which are general for building like concrete mixtures, reinforced concrete as well as the steel reinforcement are not repeated in the seismic code.

The reinforcement bar's vertical section should generally be 12 times the bar dia. A qualified engineer should validate all the technical drawings. These technical drawings with reinforcement plans should also include the bending as well as the cutting schedules for the iron workers to follow to prevent wastage. A detailed inspection of the site should be done before the casting of concrete for the installed reinforcement bars as well as the cleanliness and the quality of formwork used.

The reinforcement bars bend end can subject to crowding at the corner of a RCC structure when the floor beams are found to be joint at the column which is at the corner. When a problem like this arises, a structural engineer has to identify which of those horizontal bars are to withstand/resist the max. moment forces. If there is an overloading case at the time of a seismic event then the first to fail/bend should be the end of the beam before columns of the building.

FIGURE 3.11: Improper detailing leading to reinforcement overcrowding (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The 4 issues exhibited in the above picture is as follows: -

- The steel bars used in the columns are smooth and softer than the ones utilized in the beams. The columns are less strong as well as stiffer than the beams.
- The good filling of concrete can be disturbed by these end bends of the beams.
- There is a lack of stirrups at the ends of beams or the columns.
- Due to the integration of the floor to the beams, this will result in enhancement of stronger as well as the stiffer beam than the columns.

At the time of a seismic even the short columns are likely to fail at the top and bottom resulting in collapse. The following diagram shows the process of the breakage at the time of back-and-forth movement during an earthquake. Taking this process in consideration when in reality this cycle is repeated continuously as a series of shockwaves are generated during the seismic event which will lead to the collapse of the column with which it brings down the building.

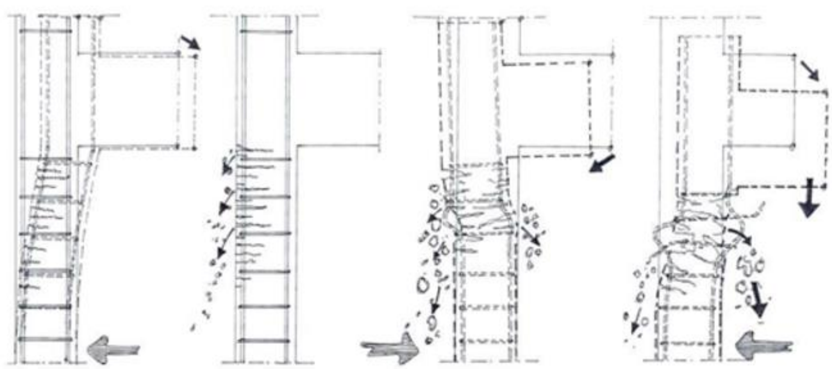

FIGURE 3.12: Weak column strong beam effect leading to structural failure with an earthquake (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The following cycle shows the progressive of such failure

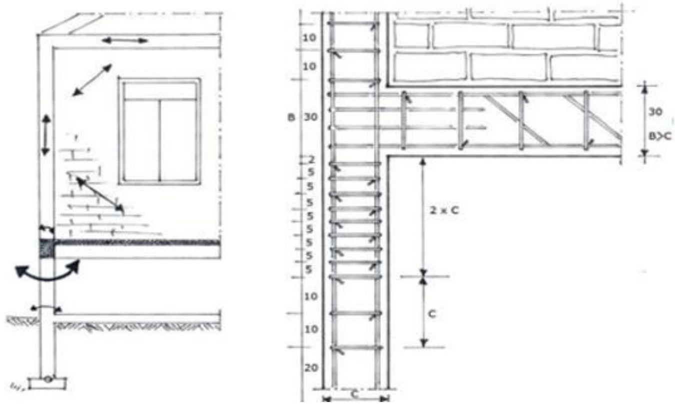

FIGURE 3.13: Advantage of masonry infill's to support columns maximum during an earthquake (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

Generally, the columns at the ground level often have the same reinforcement as well as the cross section as the ones in the above floors of the structure but it will have the full load of the building. As per the seismic code a column needs to have caging to prevent it from collapsing.

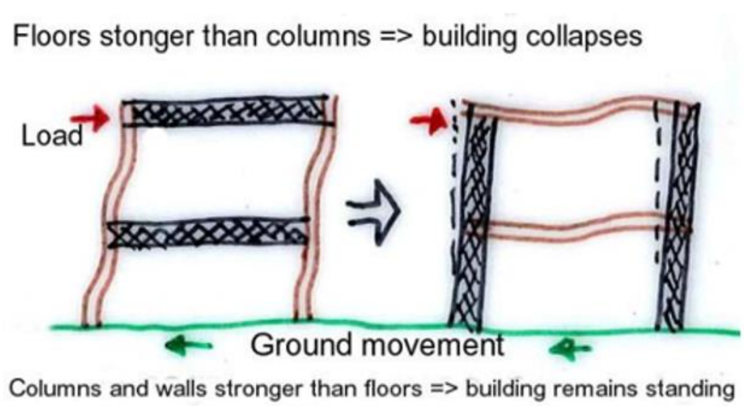

FIGURE 3.14: Schematic of a mechanism when columns are stronger than floors (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The construction of the beam floor compared to the column as well as the wall structures should be more flexible or more ductile as per the earthquake technology. The collapse of the building is imminent if the shear walls or the columns will fail. The people can exit the building when the floor beam is cracked or bend due to the failure and it will hang between the building's columns.

Contractor faults:

RCC is often called as the modern building material. However, it is not suitable for a lightweight construction due to its heaviness. The quality of RCC constructed purely depends on the location as well as the design of reinforcement. Moreover, the quantities of water and cement used, method of casting, aggregate composition and curing adds to this norm. The concrete will not attain its required strength even if the design was good but there was lack of workmanship. This is because the intended interaction between steel and concrete was not achieved leading to the lower strength structurally compared to the design proposed.

Apart from the mentioned problems which may lead to failure there are other reasons due to which a building may fail even of the maximum Seismic design forces are considered. If the collapse of a structure is studied, we can comprehend these other reasons as well. After an extensive study of such we may be able to draw methods to improve the construction process entirely so as to avoid similar future disasters.

The technical design:

The architectural designs may not always be in coherent with zones of higher seismic risks. In dew countries the architects depend on the engineers to fix the architectural designs hence they are often modified to be stronger as per Seismic Code. However, in some countries there is always a lack of coordination b/w the engineers and the architects but it is always the engineer's duty to achieve the correct design strength of a structure.

There are engineering errors caused in the placements of correct reinforcement bars at the correct locations needed. The drawings needed for the purpose is not individually detailed to attain the results. The specifications needed is to be presented in the drawings approved and it needed to be reflected in the building site as well. The site inspectors as well as the construction workers should be able to read the drawings provided.

For those RC buildings the architects neither the draughtsman provides the detail for reinforcement or make a detailed chart for cutting and bending of the steel bars.

In rural areas the buildings are built often on the basis of the contractor's experience and not using the structural design or calculations for the specific site.

The construction work:

1. In most cases the building contractors do not follow the specifications needed it require for the building like quality of steel to be used or the dimensions to be followed or even reduce the number of required bars. During a problem in the site the contractor tries to solve it onsite rather than consulting with the engineer in charge.
2. The use of inadequate aggregates quality like dirty sand, weak stones and salty water as well as using hand to mix or even not maintaining the water - concrete ratio. At the time of extreme weather additives are added excessively which in turn effects the quality of the cement. Improper curing is yet another factor to add to the list inadequacies occur.
3. Improper cleaning of formwork to be used as well as the poor quality. These may result in the residues to remain in the formwork when using it for the next construction project. The materials like binding wire cuts or dirt to remain, spacers which are not placed properly which may cause corrosion in the long term.

4. The freshly cast concrete are not vibrated properly or maybe even avoided at times which leads to the low-pressure resistance or may create the honeycomb around the reinforcement bars.
5. Following the wrong sequence / steps of construction.

Inspection of the work:

In most cases the inspections are done late or not done entirely. The inspections report is stamped and given even without physically visiting the site. In rural places the control system is often poor or even non-existent. It common to find that the inspectors being paid off by the contractors.

User modifications:

After the construction and occupying the building, the owners make these modifications which are non-approved or even do it without the consultation of the engineer in charge like the removal of the shear walls so as to create a larger opening to make space for other rooms to accommodate garages and shops.

After the construction of a multistorey structure is completed, sometimes the height is required to be increased on the owner's demand thus affecting the load factors on the building.

The following pictures are some of the damages caused due to the incompetency.

FIGURE 3.15: Modifications by Users without consulting Engineers increasing the slab thickness leading to collapse (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

FIGURE 3.16: Modifications by Users without consulting Engineer's absence of shear walls leading to collapse (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

<u>Constructional/Design mistakes:</u>

In the following picture the building was encountered with a dilatation joint which was a design mistake. This resulted in the horizontal movements differently at the two sections of the building. The minimum space to be maintained between the buildings with respect to the height as per the seismic code where kept. However, the line of the columns supporting the structure failed which led to damaging the roof.

FIGURE 3.17: Improper engineering designs leading to collapse (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The diagram shows the detail of the design of the building's upper floor where in the columns were constructed on the other building section. But there was movement of the building during the earthquake which was independent and different which resulted in breaking of the column then the roof.

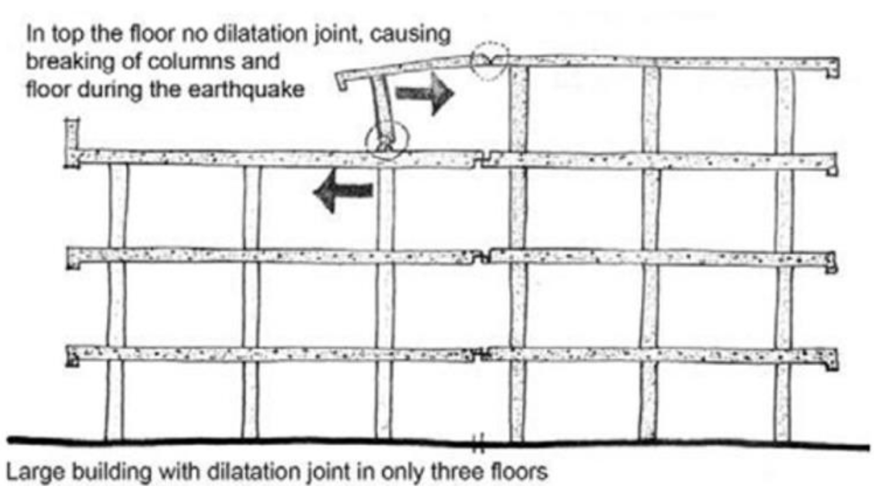

FIGURE 3.18: The roof being supported by a cracked column (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

As per the following image the column base had no additional stirrups to realize a confinement. This was found to be true in almost all the column sections of the respective building. The collapse would have been assured if the earthquake had a slightly higher magnitude than the actual one.

FIGURE 3.19: Improper detailing of column base (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

A heavy structural section was placed above the main entrance of the building. Due to the earthquake the vertical movements resulted caused larger additional forces to be encountered by the column. The designed column was incapable of withstanding these forces and lead to collapse as shown in the image.

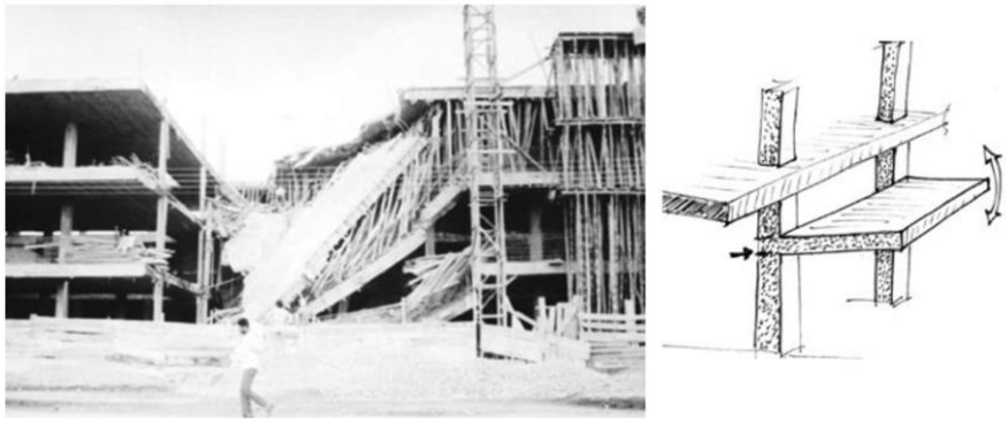

FIGURE 3.20: Improper detailing and design causing structural failure (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

The following are some of the steps could have taken which could have avoided this catastrophe.

- A proper design of the structural material to withstand the seismic forces as per the records of that region.
- A lighter construction approach which will significantly reduce the earthquake forces.
- Avoiding the awning the suspended section causing much lower forces over to the column
- Considering the awning to be separate off from the structural column.

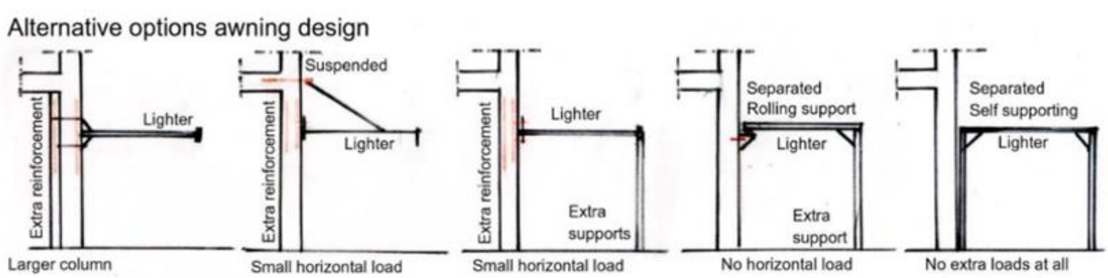

FIGURE 3.21: Engineering design options for awning design (Reinforced Concrete Construction Failures Exposed by earthquakes and other)

Structural Safety Norms to be followed:

When a building collapses the structural; safety issue gets into attention, particularly the reinforced concrete of the construction. At this point many things like design and constructional adequacies and even corruption during the construction stage come to light. Therefore, after a building has failed and collapsed, elements which are related to its which are in between using the building codes for designing, control and quality of the construction works will have to be executed properly. The earthquake as a whole cannot be avoided as it happens unannounced but it brings out the errors which have been made during the stage of construction and designing process. It has to be noted that the designing process has to keep up with the latest updated building codes which are reviewed and approved for the use. It is highly unlikely to educate the whole population about the building codes which would require actions at various levels where in the legislative system would have to be an integral part. Therefore, a National Building code has to be established with latest norms and safety measures for the right execution of a construction work.

3.3 Types of Conventional Techniques in Seismic Retrofitting [10, 13, 16 & 23]

A seismic resistance of a structural element in this method is achieved by sectional enlargement. It consists of adding concrete around the existing structural element This one of the conventional and the oldest approach for seismic resistant as Strengthening. Such methods have been implemented extensively in the joint strengthening, bridge deck as well as column wrapping. One of the most go-to advantages is that it is an easy fix as well as its cost-effective. However, the work-labour is difficult

Local method

Traditional concrete

For many decades use of the traditional concrete have been extensively adopted for the Strengthening purposes. These are utilized for the column reinforcement by themselves. It also can be that the gravity designed frames Strengthened using the method. This approach is also used in the building foundation as well. This method is used when additional strengthening is needed for a structure. As per seismic effect concern, the columns of a building or a bridge are often susceptible to the damage hence it would need the retrofit contingency. Use of traditional concrete has practiced for many decades. An extensive studies and researches have been carried out for other methods of strengthening however this approach has been efficient comparatively.

Diverse circumstance and distinctive detailing (non-damage vs. pre-damage) were subjected to test and the outcomes indicated that those columns which have been Strengthened showed higher quality strength and durability as well as stiffness with an efficient dissipation of energy They likewise demonstrated that detailing as well as the original condition of the column did not have a lot of impacts, however that what was significant was acceptable surface readiness. Another column variation Strengthening is wrapping where in which added transverse and longitudinal reinforcement concrete jacket in post-tension of the new longitudinal reinforcements.

Enlarging the structural elements have likewise been demonstrated to be effective for the seismic retrofit wherein the buildings were only designed to act only on the gravity loads. those structures are exposed to soft story collapse systems, which originate from a combination of strong beam and weak column. The objective of the retrofit is to change this framework into a combination of strong beam and weak column conduct which is best and should be possible by adding reinforcing to the sections.

Foundations are another structural element that can follow this method for strengthening. The prescribed retrofit is an addition of a concrete layer to the topside of the building's footing A subsequent increase of the shear resistance will be enhanced, by both taking into consideration the negative moment strength generation due to the addition of the reinforcement at the top wherein the effective depth is increased which in turn will enhance the positive moment capacity increase. Those vulnerable footings which are susceptible to the overturning the use of retrofit is to enlarge them. If it's not available then adding additional pile or by tying them downs is recommended.

Shotcrete

Recent advancement in area of section enlargement is shotcrete. It is projection of the concrete or mortar pneumatically at high speeds over the section’s surface. It was presented in 1911 and has been utilized in retrofit applications for more than 50 years.

Carl E. Akeley the development of the shotcrete gun. shotcrete is available in the form of wet and dry mix.

FIGURE 3.22: Representation of application of Shotcrete (Techniques of Seismic Strengthening for Concrete Structures)

Principle advantage of Shotcrete is the advantage it facilitates of utilization particularly in difficult to get to zones which bring about a decrease of time and cost of the construction. It has a thick composition, low permeability as well as low shrinkage which extrapolates its durability. The primary detriment of utilizing shotcrete is that special method of work procedure and attention is demanded all together to accomplish a quality product.

This special approach includes placing thick sections in layers, using of a blow-man to help reduce rebound, utilizing of a blow-man to help decrease bounce back (when the shotcrete hit a hard surface a portion of the bigger total will in general ricochet and assemble in a similar spot), and requiring quality control and assessments. At last, it ought to be noticed that with shotcrete, likewise with all methods of fixes, consideration must be given to existing concrete’s bond area and to the surface readiness

Polymer concrete composite

The utilization of Polymer Concrete - PC is yet another improvement in the field of concrete. Polymer Concrete is produced using a polymer cover which is usually a thermosetting polymer which is blended in with a mineral sand or mortar, mineral filler, or aggregates, gravel, or crushed stones instead of concrete. This material has a few focal points, for example, high resistance to chemical and abrasion, high strength as well as low permeability moreover good adhesive properties. Like in any case, there are impediments are:

- cracking due to restrained volume changes
- poor resistance to ultraviolet light
- creep at high temperature
- additional cost

It is utilized in the re-emerging / resurfacing as a compound in the fix of concrete structures as well as in the deteriorated structures. Despite the fact that it exhibits many favourable circumstances Polymer Concrete is more costly and doesn't tackle the broad work issue of utilizing standard concrete.

High performance fibre reinforced cement composite

The use of fibre-reinforced concrete and high-performance fibre reinforced cement composites are the later advancements in the field. The definition of high-performance fibre-reinforced cement composites are those components which are displaying a post-top strain hardening response related to high energy dissipation which is a quasi-strain hardening behaviour as well as numerous cracks. Benefits of utilizing such materials are enhancements in toughness, ductility, absorption of energy as well as cracking shear resistance. They are likewise acceptable in obliging thermal expansion, differential elastic modulus, and good ductility as well as an excellent small width distribution of cracks. In any case, by default, the initial price tends to be on the higher side because for the high labour work involved in the job. Slurry infiltrated mat concrete - SIMCOM & slurry infiltrated fibre concrete - SIFCON are the two good examples of high performance reinforced concrete material.

Slurry infiltrated mat concrete is simply pre-placed continuous stainless steel fibre mat infiltrated with a cement-based slurry. These mats are pre-manufactured and brought to the site in huge rolls. The pre-manufactured have those benefits of placing fibres by providing an environment which is controlled. This takes into consideration the addition of the strength by the specific orientation of fibres with mats during its construction However, the method involved is less complex than typical reinforced concrete since there is a diminished amount of framework.

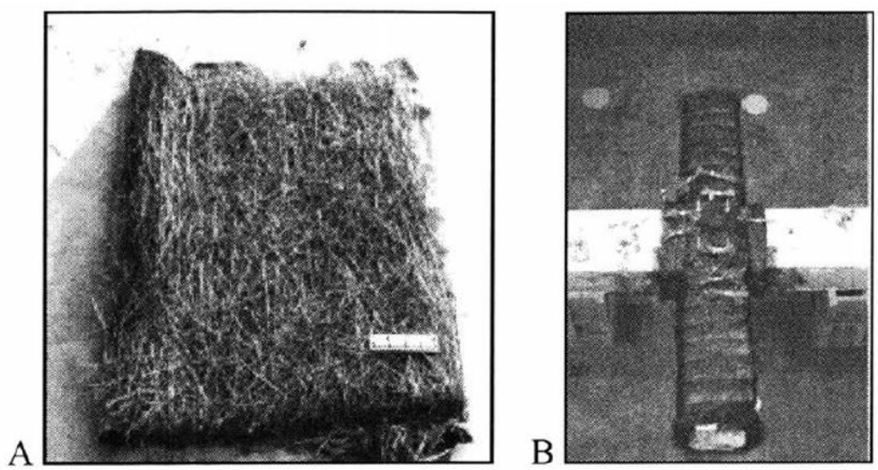

FIGURE 3.23: SIMCON (Techniques of Seismic Strengthening for Concrete Structures)

A pre-set short steel fibres of Slurry infiltrated fibre concrete are then penetrated with cement-based slurry. In this technique, the fibres are put on site with the end goal that their orientation can't be controlled and required greater volume of fibre. Regular applications are the connections between beam to column as well as wrapping of the column. They bring about a hike in the capacity of absorption of energy as well as in the strength of those members which are strengthened.

The benefits of such techniques are a benefit of less difficulty in labour compared to a regular steel jacketing nor are a concrete work as well as a standard method and equipment of construction being incorporated. It should be noted that this method is still new which needs to be enhanced further which would have a great impact in the field when the required research is finished. Microfiber high performance reinforced concrete has many examples of its use one such is the necessity of thin repairs. Since these repairs does not have any load-bearing property often pose a difficulty to do the work, however strain compatibility plays an important part which would result in a high-stress development.

The 3 properties are indeed needed are: -

- the ability to stop degradation of the existing structure especially steel corrosion
- the creation of a proper bond with the existing structure
- the durability and capacity to withstand sever climatic conditions

Addition of steel

This method of steel is often achieved by the addition of jackets or plates form. In the technique of external prestressing tendons of steel are also preferred. The benefits of utilizing steel incorporate that it doesn't add to the weight of a structure or over to the footings relative to the use of concrete moreover it saves time of construction like there is no curing time. Yet another advantage of the method is that the installation is rapid without interfering with the building occupants and the members are pre-fabricated offsite, unlike other methods. However, there disadvantages to this method like

- Steel can be labour-intensive
- Time-consuming
- Require heavy equipment to handle thousands of tons
- Having more difficult maintenance.

An average of 2.5 days will be required for Strengthening of a typical column which does not include painting as well as excavation of the site. The demand for the design of retrofit is on the basis of site installation compared to what actually is required. One of the problems is that the steel required could wind up being stronger and heavier than the retrofit prerequisites to keep it from buckling under its own load during lifting as well as placing. Every component must be restricted in their estimated size and splices requirement and designs which are more complicated are employed so as to reduce the difficulty in carrying. The requirement of maintenance, especially protection from corrosion is indispensable for steel. It often results that steel is a costly alternative.

Steel Jacket: Column

The steel jacketing technique can be employed for joints and columns. Firstly, the Strengthening of a column are discussed. In 1971 after the earthquake in San Fernando it was recognized that the reinforced columns are the ones to be considered more important. In the context of columns of a bridge, column Strengthening was extensively analysed and studied using steel jackets during the 1990s. The initiator of this particular research was credited by the California Transportation Department - CALTRAN. This research/experiment on this method of steel jacketing resulted in the overall enhancement of the structure such as the increase of shear strength, ductility, and dissipation of energy significantly. Hence due to this reason it been extensively utilized in the U.S as well as in Japan. The fundamental of the use of this method being efficient compared to other methods is that it provides a sort of a passive confinement reinforcement. The steel jacket will also help the concrete from dilating. It forces lateral compression, as well as compressive strength, is increased. This also results in an increase in its effective ultimate compressive strain as well as ductility. In the case of a circular column, these steel jackets are in two semi-circular half-sections wherein it is site welded along the column with the height of the jacket. A gap/space of 2.5cm is maintained between the jacket and the column. A composite behaviour and a good bonding are thus achieved by the use of filling cement-based grout. It is to be noted that using an expensive grout may not enhance the required performance instead of using a cement base. A space/gap of 5cm is left between at the column's bottom and the footing's top to avert bearing it may pose to the steel jacket on the footing. However, for rectangular columns, the geometry options for the steel jacket are a rectangular jacket, circular or elliptical. If the rectangular type of jacket is followed then the steps will be the same as the semi-circular type of jacketing which is already discussed in the previous sections except L-shaped panels has to be site welded. For those following the circular or elliptical type, the filling should be with concrete rather than using the grouts due to the larger gap created between the jackets and the column. These methods are depended on the type of application's condition as well as the mechanism of failure either a partial jacket or steel collar is utilized.

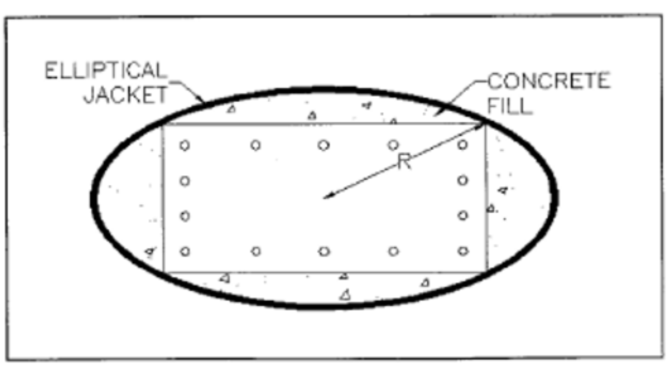

FIGURE 3.24: Rectangular section strengthening (Techniques of Seismic Strengthening for Concrete Structures)

It has been to be noted that the requirements as well as the design of the steel jackets are based on the shear, flexural or the failure mode.

Vertical earthquake motion:

At the point when a structure is exposed to seismic loads, it will chiefly be exposed to a huge horizontal force. Yet, in a seismic event, a part of the load likewise originates as a vertical load from the ground. It is assumed by most codes including the American Concrete Institute - ACI that these loads are balanced by the gravity loads of the structure. It has to be noted that the surveys are done after a seismic event has detailed a vertical movement of ground motion's beginning. It has also been reported that these vertical motions might be the reasons for circumferential cracks in reinforced concrete piers and columns. The research and analysis of the steel jacket over the column and piers with a vertical impulse motion has proven to be effective.

Steel Jacket: Connections

Providing a corrugated steel jacket to confine a connection week is one of the possibilities of rehabilitation techniques. The jackets for the connection retrofit follow the same method as the column retrofit which is site welding jacket of two halves Similar to the column jacket the gap then produced is filled with grout which would provide good behaviour of composite as well as continuity Most important benefits of using a corrugated jacket compared to a normal one come from an earlier confinement effect. Which is when a flat steel jacket is utilized for reinforcement the jacket will not provide the required confinement till the expansion of concrete is made i.e., the core of the concrete becomes plastic. The use of corrugated jackets tends to have an axial rigidity which is smaller which would result in the non-existence of lateral expansion while the steel jacket is loaded in the axial direction. The effect of confinement laterally is produced in the initial phase of the loading at the point where the concrete is at its plastic stage the jacket installed should be extended towards those columns above as well as below for a distance min. equal to the length of the joint so as for the steel jacket to be effective. The practice of this technique is effective for both column or beam confinement It ought to be noticed that on account of beams, a gap should be given between the beam and the jacket to limit flexural strength improvement, which would make extra forces produced in the joint and in the column. This method is also applicable to the beams as well.

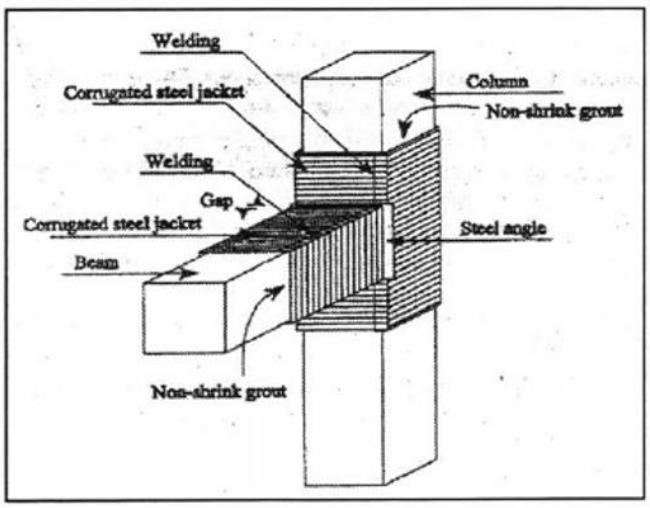

FIGURE 3.25: Strengthening joints using corrugated steel (Techniques of Seismic Strengthening for Concrete Structures)

Steel Plates

In both Germany and Switzerland in the time of 1960s, a technique of bonded steel plates was practiced to strengthen the structures made of concrete. This particular method was rather simple where a two-component epoxy adhesive was used in the bonding of steel plates and the concrete thus creating a composite system of a three-phase concrete-glue-steel During the placement of the jackets, these few important elements are to be maintained Firstly the surface of the concrete structure intended should be cleaned after which epoxy should be considered maintaining the strength of epoxy to be greater than that of concrete due to which when failure may happen it should be in the concrete area. Lastly, the steel plate used for the method should be thin as well as long to keep away from brittle failure of the plate. The assembly can also have an addition of anchorage like bolts which can be utilized at the beam end. However, the drawback of this particular procedure is steel's weight at the time of construction as well as placement. It also demands for support system during the stage of bonding. Corrosion and the protection of fire is yet another problem which the steel is subjected to which has to been taken care of.

Beams

By attaching the steel plates to the beams tension side, it has resulted in the application of research as well as in the field that the flexural capacity and stiffness are increased at the same time decreasing the crack and the deflection experienced in the beam.

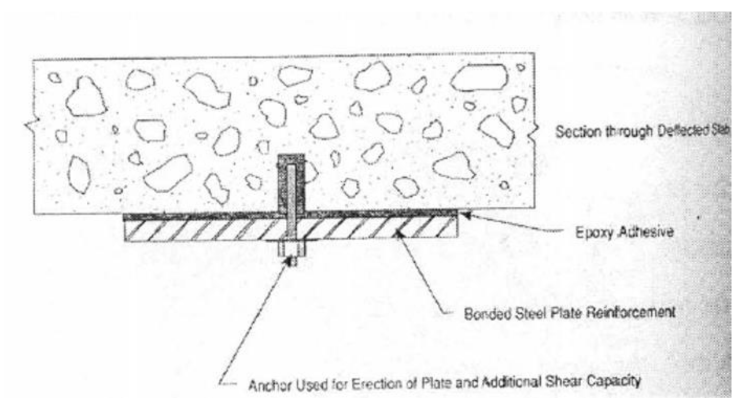

FIGURE 3.26: Strengthening beams using steel plates (Techniques of Seismic Strengthening for Concrete Structures)

Deficiency in the coupling beams can be found. By fixing a thin steel plate to retrofit the coupling beam over one side has shown to have increase in the beams shear capacity from the experimental research point of view. The practice of this particular technique/method is found to be convenient since it does not interfere or disrupt any occupants as well as the architectural finish. Moreover, only one side of the beam is being worked on which adds to the advantage. This method of Strengthening offers an enhancement of the beam's stiffness, strength, absorption of energy, and capacity of its displacement while ensuring the plate is fixed to the beam using epoxy adhesive as well as bolts. However, this method may not work for those coupling beams which are ductile and only proves efficient in the case of the coupling beams in regions of moderate seismic events.

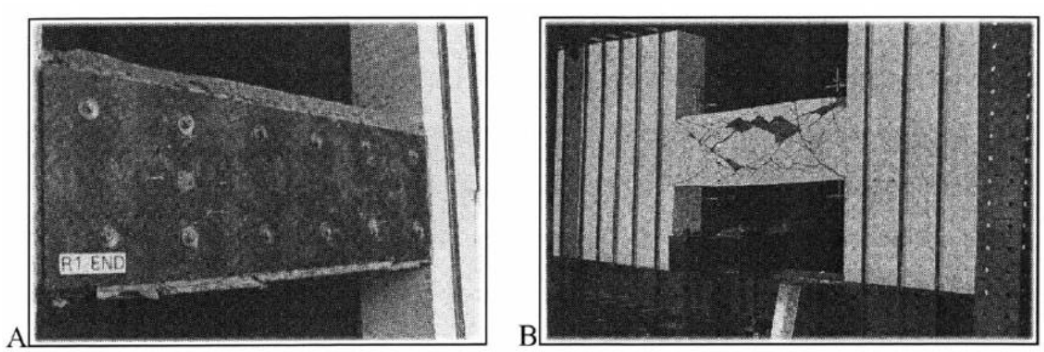

FIGURE 3.27: Strengthening coupling beams using steel plates and tested (Techniques of Seismic Strengthening for Concrete Structures)

<u>Steel Cable:</u>

Concurrently, two kinds of Strengthening can be achieved using steel cables Firstly, to confine the movement of the structure relative to its supports. Secondly, to provide an external reinforcement. The first one utilizes the steel the cable to be placed across segmental bridges hinges. The principle used in this technique is to confine the detachment of the bridge segments at the hinge so as to avoid the collapse of the structure from the provided supports. As aforementioned in the previous sections, this method was initially implemented by CALTRAN during the earthquake in San Fernando in 1971 for strengthening the affected bridges. Over 1262 structures were employed to be Strengthened using this method and it took over $54 million to complete the project in 1989. Now the second method mentioned which the technique of external is pre-stressing was already under use since the 1950s. However, the use of the method was discontinued in due course but later it was improved and re-implemented with advancements and enhancements in the field of pre-stressing. Now it is broadly used in both Japan as well as in the U.S.

Thus, many benefits offered by the method of external pre-stressing is that: -

- it uses simple construction methods
- involves fewer grouting problems
- can be inspected
- can be replaced throughout the life of the structure

However, its main drawbacks are that due to its open nature it is vulnerable to: -

- corrosion
- fire
- vandalism

The method of external pre-stressing is employed usually to counter the problems of deflection or enhancing the strength of an existing structure. Moreover, the technique also bears fatigue as well as cracking additionally. The most common application of external pre-stressing is in bridges where it placed within the box girders or at the outer area of the I-Beams.

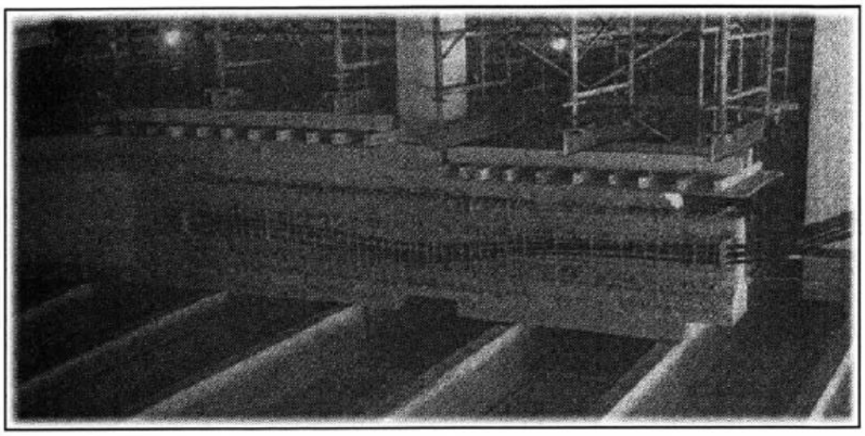

FIGURE 3.28: Method of External Prestressing (Techniques of Seismic Strengthening for Concrete Structures)

Composite Jackets

Composite materials are relatively new to the field of civil engineering applications; hence researches are still in progress. These materials are made of fibres along with resin/epoxy which makes the non-isotropic property of a composite. It should be noted each application carries a specific approach of composition as well as design which needs to be calculated. This method is rather complex and difficult which demands the details of the element's volume production, reinforcement types, geometry, tooling, and matrix type as well as the economy in the market. The composite material is often used as sheets or jackets in the field of civil engineering applications.

However, the benefit of using composite as a material is that: -

- lightweight
- high stiffness or high strength to weight ratio
- corrosion resistance
- durability
- low thermal expansion (at least in the fibre direction)
- low maintenance

This method works well with the marine environments, moreover, the work can be done without disruption to the building as well as its occupants wherein the building needs not be closed. One of the biggest drawbacks of using the composite material is its high initial costs of the material. This is due to the high modulus and strength of fibres such as carbon. However, this problem can be balanced by durability and no maintenance in the longer run. The inspection of the composite is also hard. Visual inspection has no value since it does not reveal the defects within the material. However, a complete inspection like using X-ray methods can be expensive. Since the composite material is relatively new to the field of civil engineering and is under development there is a limitation for its engineering design and code provision. Therefore, the structural engineers have to depend on the design services provided by the supplier or even develop with one's experience and research. It ought to be brought into attention that relevant guidelines and rules for design particularly for the composite materials used to strengthen concrete are set up by the relevant committees all over the world. However, this is not been published officially.

Columns:

The application for columns has the same idea as that is concrete or steel jackets. The shear strength and ductility are enhanced by the use of this method i.e.; composite jacket which provides passive reinforcement which results in the increase of confinement. It also helps to inhibit the failure of the rebar lap-slice, as well as axial strength in a member, which is also reinforced. Many systems of composite retrofit columns are available which have been tested and researched as well as showed to be effective. These can be divided into two cases, which are: -

a. In-situ fabricated jackets,
b. Pre-fabricated jackets.

The composite material is often painted after the installation to protect it from the ultraviolet light and moreover for aesthetics as well.

In-situ fabricated jacket:

One of the most favourable parts of in-situ fabricated jackets is that they can coordinate and match the state of a column correctly. Even though of this particular advantage, the method of in-situ fabricated jackets takes a longer time to be fixed and installed. It also requires special attention such as curing and on-site quality control. The finishing of the jackets purely depends on the work carried out by the field crew. These are some of the techniques followed in the application

a) At the area of potential plastic hinge sheets of carbon fibre which is unidirectional are wrapped and fixed transversely as well as longitudinally. These sheets then fixed to the column utilizing an epoxy.

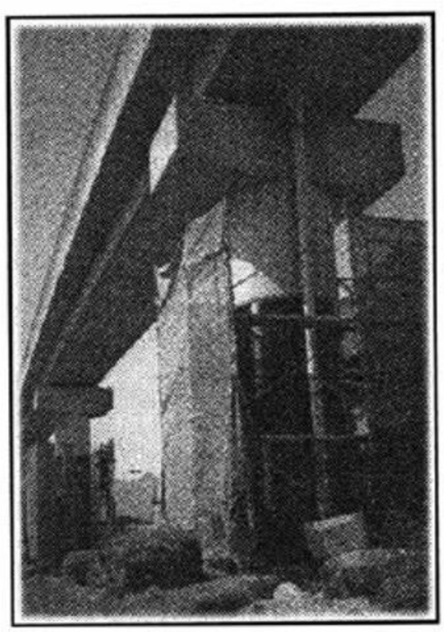

FIGURE 3.29: Method of Strengthen In situ with carbon fibre (Techniques of Seismic Strengthening for Concrete Structures)

b) Straps of E-glass fibre is fixed around the concrete column since it proved to be more economical than carbon fibre. A pre-peg or can be applied dry along with epoxy in the field. Then the entire system can be cured with the ambient temperature. One of the uncommon techniques used in this system is utilizing a glass-polyaramide-epoxy composite wrap around bladders. These are elastomeric thin bags. The columns are wrapped around with these assemblies and then injected with cement grout to stress it. With this method, a rectangular geometry of the column will have to modify to an elliptical shape.

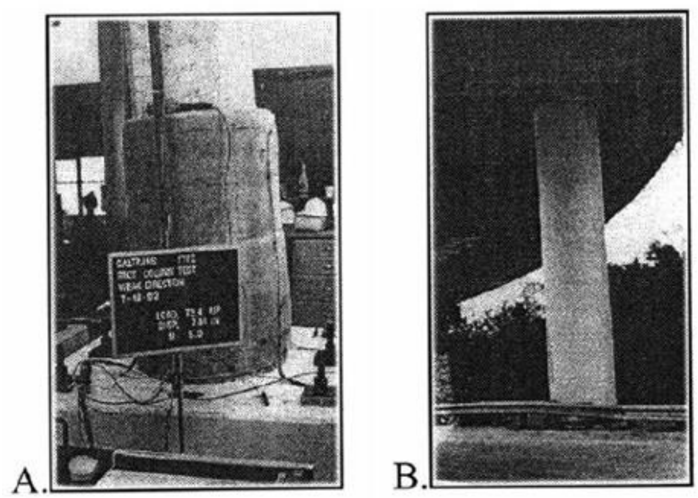

FIGURE 3.30: Method of Strengthen using Epoxy fibre glass carbon wrap (Techniques of Seismic Strengthening for Concrete Structures)

c) Automated machines are used to jacket the column continuously to wrap carbon buddle. A pre-peg tow are the fibres i.e.: A Robo-wrapper is utilized to wrap the column with a carbon fibre that has been pre-injected with resins. Thus, a hoop like a wrap jacket is then produced by rotation of the robot around the column which moves radially as well as vertically. In this particular method, it is to be noted that the quality problems are significantly non-existent. The recent development in these robots have resulted in wrapping up to 6m of columns in 2 hours. These jackets are then cured for around 8 to 10 hours using a radiant energy curing system. This system can be electrically heated blankets as well as enclosure oven on-site

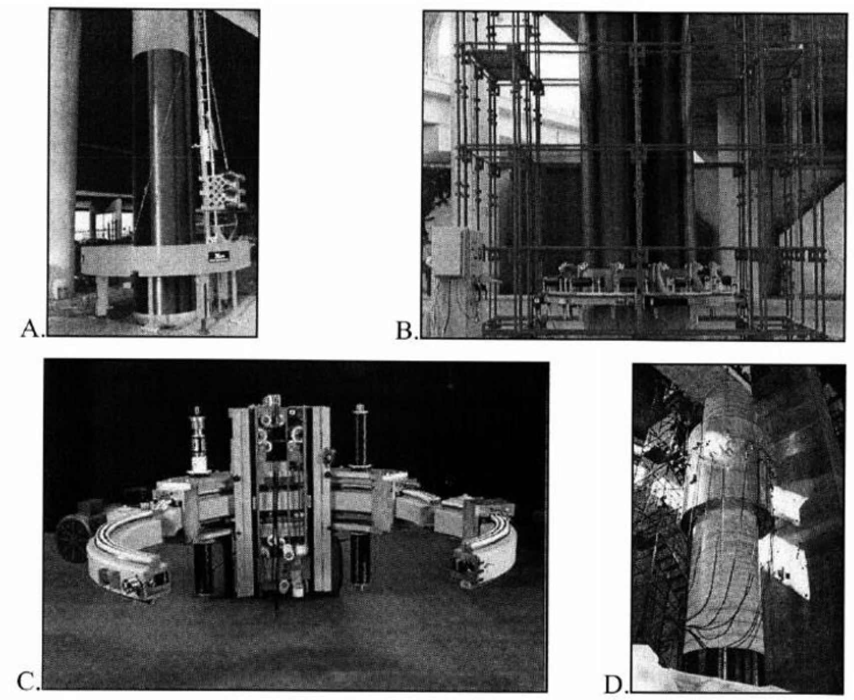

FIGURE 3.31: Method of Strengthen using Fibre wrap robot (Techniques of Seismic Strengthening for Concrete Structures)

This technique can become most economical in construction since it is not labour-intensive or needs any heavy machinery without compromising the provision of its high strength, reliability, and low weight.

Prefabricated methods

The method of prefabrication of jackets is a recent development which is still under research. These types of jackets are made for a particular column with specific geometry which is cured and made off-site. Compared to in-situ their installation is much faster and the control of the quality is found much easier in the field. It takes a special kind of adhesive to fix the jacket over the columns intended. These jackets are made into a roll which is made of fiberglass strands and sheets that is fiberglass and polyester resin jacket. Then these rolls are encased using fabrics wherein these bends only in one direction. This mat is made wet with resin and are set into the forms. The jackets are installed once the curing is over and are in the site. The bonding between the elements is achieved with the help of epoxy. The benefit of this system is that it can be fixed within 2 hours as well as load capacity is increased. Additionally, the columns are protected from freeze-thaw effect as well as corrosion.

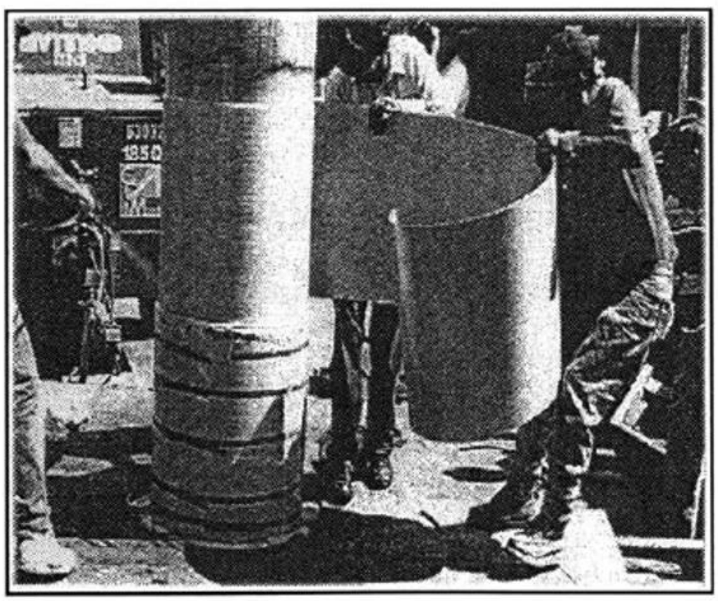

FIGURE 3.32: Installation of pre-fabricated fibre glass shell (Techniques of Seismic Strengthening for Concrete Structures)

The system of clock spring utilizes isothalic polyester resin. The required ductility is achieved with the help of several layers of shells. The curing of the adhesive applied is cured by using a clamping system that would hold the prefabricated shells tightly.

Another kind is to using E-glass fibre which is prefabricated. These are reinforced using slits to the composite shells which are cylindrical. The content of this assembly is 2 parts of epoxy and glass fibre which are unidirectional. It is to be noted that the arrangements are made where 90% of the fibres are in the circumferential direction and the rest are in the direction of longitude. During the time of Strengthening of the columns, these shells are opened. Then these are clamped onto the column which would be in sequence with their slits being staggered. A continuous jacket is formed by bonding shells to each other as well as the column with the help of an adhesive which is of high strength like urethane-based agents.

Global Methods

Shear Walls

Shear walls are by default to be used as a seismic retrofit in the recent designs as well as over half a century. Typically, the shear walls are made of concrete using the method of infill walls or precast panel with reinforcements using steel in a typical rectangular pattern, but in some cases, these are made of steel plates or maybe a masonry infill A shear wall is defined as a resistance provided by a vertical element to withstand any lateral loads in their plane which then received from diaphragms as lateral forces and then it's been transferred straight to the foundation. Apart from withstanding the overturning moment, the shear wall also subjected to the bending as well as the shear forces. At the time of a seismic event, the shear walls help the structure to withstand an overall drift as well as the story mechanism. In any case, the damage might arise it will be mostly due to the reason for shear. These failures will be displayed in the form of cracks that are in the X type pattern. The advantage of the provision of shear wall is that it is flexible and is also architectural coherent i.e., it can be hidden without affecting its properties which makes it a good solution for strengthening a historical structure even though it is expensive.

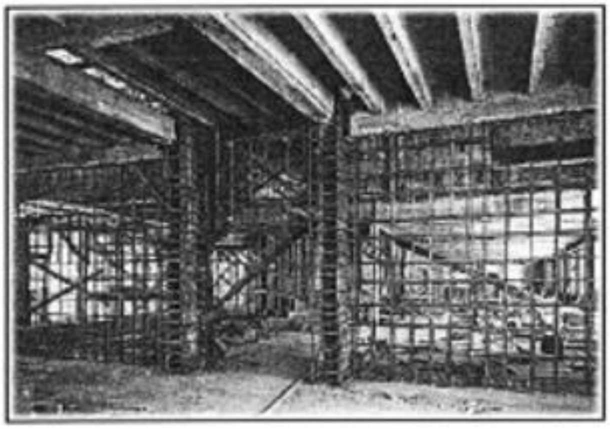

FIGURE 3.33: Construction of a shear wall (Techniques of Seismic Strengthening for Concrete Structures)

A good amount of attention required while implementing the shear wall as a solution since its design should be coherent throughout the structure's surrounding members, its connection as well as additional load it produces. The distribution has to be taken care of while designing the shear wall as it has different effects in different locations on the building. This can be illustrated using an example wherein a placing shear wall in a typical 12 storied concrete building at its outer corner will result in not providing strength or stiffness additionally while restraining the building's lateral drifts. By using the same case as an example if the shear wall is placed in the central bays, then it will produce a surge in the strength and the stiffness. Dowels are used to make the connection between the shear wall to the existing surrounding columns as well as the beams as mentioned in the above sections while implementing the shear walls system existing connections surrounding the wall should be taken care of such that the connection should be working for the intended use as well as strong enough to bypass the forces from and to the wall. After installing a shear wall additional loads will be generated. It also changes the load paths which then the building would need to support these loads which initially was designed for. Hence these structural elements need to be analysed as well as possibly Strengthened. Lastly, the solution of the shear wall will create dead loads additionally into the building. That would have an effect on the building as well as its foundation system.

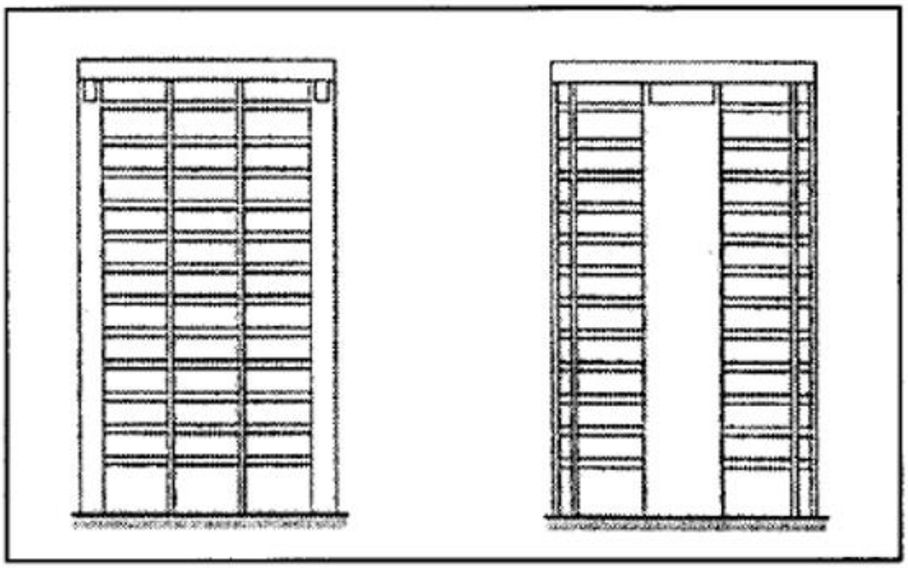

FIGURE 3.34: Distribution of shear wall differently (Techniques of Seismic Strengthening for Concrete Structures)

Dual Frame Wall System

In this particular system use of the shear wall as well as coupling beams are being utilized. Hence this system is called a dual shear wall. The uniqueness of this technique is where more than one wall which is in parallel, moreover these are connected by a short shear yielding coupling beam and maybe a longer flexural yielding fame beam. During an event of an earthquake, lateral loads are applied to the system. This affects the walls which would laterally be displaced in the direction opposite. Thus, at the ends of coupling beams creating a vertical and displacement opposite. Hence during this action, the beams are forced to yield even before the respective walls start the energy dissipation. The design of this system is made that the involved coupling beams will yield at the same time. After the process, these beams are softened which will trigger the cantilever walls to bear the additional loads. This is continued until a base yield is developed. The major benefit of the dual shear wall system is that a spread of the plastic action is circulated to the entire structure in turn the beams and the walls involved will take the intended damages thus helping the building's rest of the features from getting affected.

The following picture is a medical centre in the USA which has been seismically upgraded using the system of shear walls. The structure was built in 1936. The parameters of the building are RCC columns are the supports with RCC beams with a one-way concrete pan joists floor. The exterior shear wall was the solution selected for strengthening this building. Choosing this option turn out to be the most economical as well as least disruptive to the building. The shear walls were placed inside of the brickwork within the building exterior.

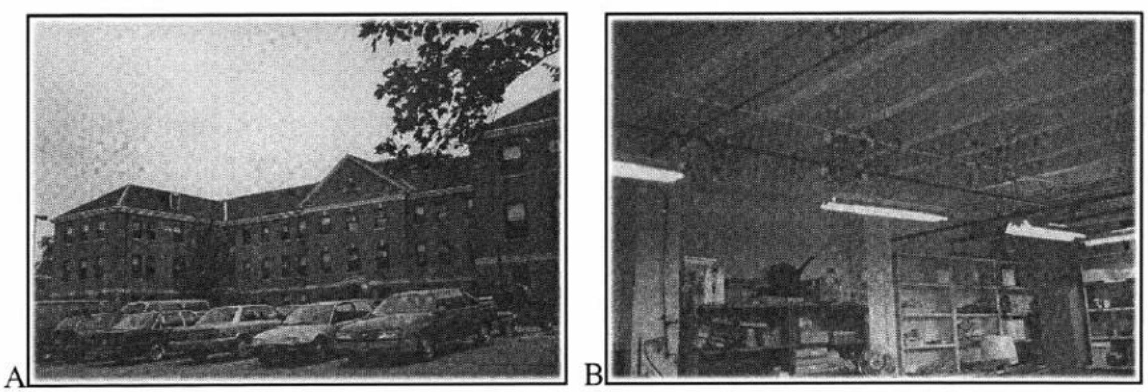

FIGURE 3.35: Schematics of Building (Techniques of Seismic Strengthening for Concrete Structures)

<u>*Steel braces*</u>

The building's structural strength, the story drifts resistance, as well as stiffness, was significantly improved with the addition of the steel braces since the structure has a non-ductile RCC. The introduction of bracing using steel has been widely used for over 50 years. This technique has been proved efficient. This is due to the reason that the overall strength of the steel brace system/frame of concrete is found to be more compared to the combined effect of the concrete and steel system. The benefits of the steel bracing system are that it allows for openings without many disruptions, relatively a lower amount of weight is experienced with the steel bracing system comparatively to the concrete shear wall. Moreover, their distribution flexibility which can help in avoiding shear concentration problems since the placement of steel is applicable throughout the structure. This external system of steel bracing gives an added advantage of working outside the building without causing much interference to the occupants as well the building itself. Due to the exposed members of the steel bracing system, it needs to maintain time to time and the initial cost executing the steel bracing is little on the higher side which is its major drawbacks. Few of the different bracing systems are: - a) Post-tensioned b) concentric-X-shaped c) eccentric-K-shaped These systems are achieved using the: - a) L-profile sections b) double angles c) tubular profile sections the concentric system resulted in the highest strength through a study of an experiment. At the design stage, many parameters have to be noted and work as per. Such as checking the yielding as well as the buckling parameters of the members used for the bracing system Moreover, extra needs to be given to the connection incorporated to ensure the load transfer between the steel and the concrete safely. While incorporating such a system the building will go through certain load transfer changes in the structure which is existing. Hence these members' reactions to these changes should be particularly studied and designed respectively. The changes like when there is a controlled lateral drift, the forces in the steel brace such as axial force will generate an adverse lateral force in those concrete members which are existing. Hence under such changes, the respective column will experience loads that would be more than its axial capacity which may be either compression or tension. Which would result in the need of strengthening the column. A research done by H. Abou-Elfath and A. Ghobarah concentrated on the concentric frames as well as its behaviour. The study involved in those parameters such as the bracing amount and the distribution of steel of a specific frame need. The following diagram represents a typical steel bracing system, which is distributed along the base of the building's overall height.

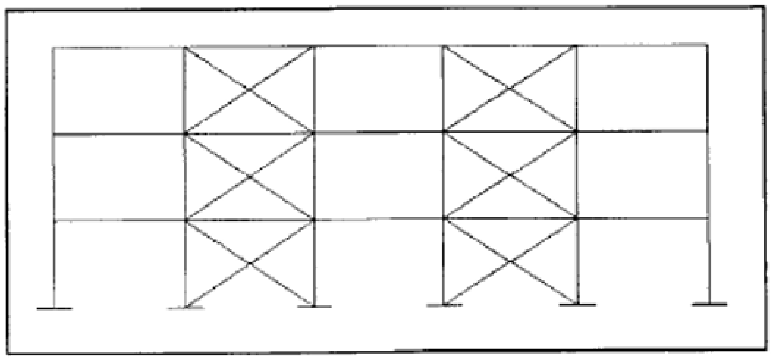

FIGURE 3.36: Configuration of bracing typical (Techniques of Seismic Strengthening for Concrete Structures)

The study also included in different placement of steel bracing into different bays of the structure. Even though with the adoption of a typical bracing configuration which has the ability to provide an added strength as well as stiffness this may not prove to be an optimal method for the distribution of bracing. The building's plastic mechanism can be improved such that a configuration of bracings can bring about the contribution of the stories to the overall deformation. Those configurations which might change the stiffness of the building suddenly such as a one-level bracing should not be incorporated. The research's second part was about the behaviour of the bracing amount. This resulted in the fact that as there is an increase in the amount of steel used in the brain system it significantly enhanced the building's performance as well as the demands of seismic because of higher stiffness. An added advantage in the increase in the amount of steel in the bracing system is that there is a reduction in drift which results in lowering the damages caused.

Post-tensioned Systems

In the system of post-tensioning, the members used in are rods that are pre-stressed initially. One of the major benefits of suing such a system is that diminishes the shortening of the brace where it may slack. Moreover, there is an advantage of minimized lateral stiffness due to the tensioning of the brace. Lastly, at the higher level of the pre-stress of the brace, it may result in yielding of the brace thus allowing the dissipation of energy majorly with a lateral drift being relatively small. The most effective response of the brace as per research is when the pre-stress level is employed at the yield strength of 50% or higher. While the pre-stressing is employed it should be noted that the surrounding members are affected as well. The forces from the pre-stressing which are experienced by the columns which are adjacent would create a higher demand for shear. Therefore, at the time of a seismic event which would result in requiring a high shear. Thus, the column which are already under the use of pre-stress bracing might fail prematurely due to the added requirement of shear demand during the earthquake.

Base isolation

The system of isolation is one of the old techniques wherein it limits the interaction b/w two systems. This particular strategy has been in use for more than 70 years. It was initiated to resist or isolate the machinery which causes vibration from its respective surroundings the isolation technique is a recent introduction to the field of civil engineering. It also has gone through a lot of developments since the times of its introduction. When this isolation method is employed in a building for the seismic requirement it resists the motion evolved from the ground. This process is achieved by utilizing bearings. These are typically placed at the level of the basement which would in between the structure and its foundation. The isolation base is located under each column in a frame. In continuous structures, these are placed in a maximum allowable space. Base Isolation is achieved when the following 3 steps are accomplished: -

a) There is a need for change in the fundamental frequency of the building itself and has to be kept apart from the seismic excitation frequencies which are typical to those areas. To achieve such a method the base of the building has to increase its flexible characteristics which is in the horizontal direction to reduce the generated resonance and then decrease the floor acceleration.

b) The dissipation of the energy generated has to be reduced to avoid the damages from the earthquake on the structure.

c) Even the lateral loads which are minor has to be taken into consideration as well as to provide to that energy dissipation or the rigidity due to it.

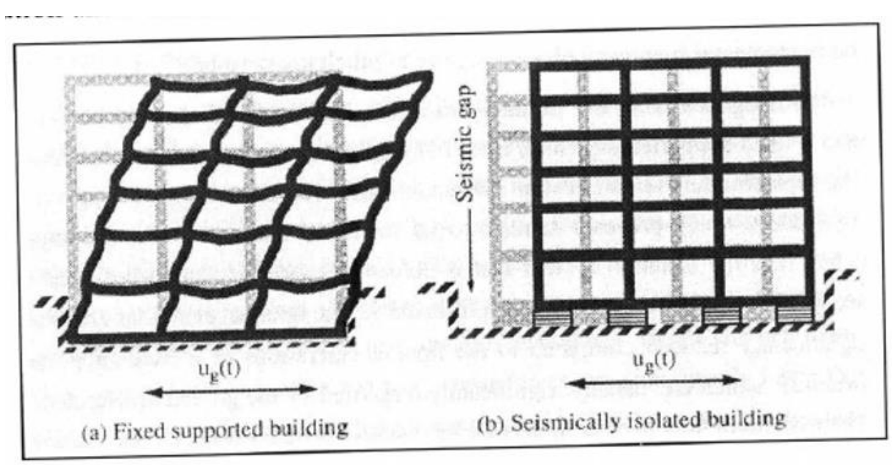

FIGURE 3.37: Fixed support structure vs. Isolated Structure (Techniques of Seismic Strengthening for Concrete Structures)

It is proven that the structures with base isolation should an improved performance during a seismic event than the conventional buildings. This technique has been widely used as a seismic solution in USA as well as Japan.

The following constraints limits the base isolation: -

a) Due to the possibility of substantial displacements, it is to be noted to provide suitable accommodation that this method is possible without causing any damage which is creating a moat around the building. These aspects have to be assured to stay through the entire life of the intended building. Moreover, considering the generated vertical forces have to be given. At the time of a seismic event, the building will go through forces generated in the vertical as well as a horizontal direction. The vertical forces from the earthquake are often thought negligible but this has to be accommodated for in the design. Most of the isolator thus designed is not for them. These problems of the vertical forces which are small can be solved through a detailed connection as well as an isolation distribution. However, the vertical forces which are large in nature for those buildings with a high overturning moment may not be solved by just in detailing and even by the use of isolation.
b) At the time of considering the base isolation method, if the building is already designed to be flexible then enhancing its flexibility further will not improve the situation. These are the limitations thus need to be noted while employing the method of base isolation.

The structures which work efficiently with this system are those ones which are low to mid rise buildings like 10-12 levels of floors with clearance of 10 to 20cm in their surrounding as well as service later in addition, the supporting soil of the building should have a good stiffness which also has to be accounted for. The higher the stiffness of the soil the better is for the system. Lastly, as per the last two limitations, it is to be noted that high rise structures are to be avoided for this particular isolation type.

The drawback of base isolation is it's a recent method of approach to the structures. Even if this technique works efficiently at the time of an earthquake in some countries or areas the only a few systems might experience in the field. Quite a large number of tests have been carried out in the labs, to quote an example during in the seismic event in 1996 by CALTRAN many different systems of the isolations were employed, however, there are still studies which needs to carry out to learn the field behaviour exactly. Many problems which the building may face like the effects of ground motion acceleration on upper levels of the building since the epicentre is much closer on the system as well as the conditions experienced in the field still need to be sorted out.

The method of base isolation has been utilized in recent construction as well as retrofits projects. The related examples will be addressed in the next section for a better understanding. However, the benefits of using base isolation are:

a) It has a relatively lower disruption/impact on a structure which is existing.
b) For the structure which is intended for the method stiffness or the strength additionally is minimal. Mostly this method is carried out at the basement level which will not affect the building occupants. This criterion is much important for the historical buildings which should avoid disruptions due to the elements which the building carries like ornamentations and other features.
c) The highly-sensitive buildings which cannot afford any movements such as hospitals will be a good option for the base isolation method.
d) An added benefit of utilizing the base isolation is that accommodating the torsion was in through designing bearing locations to bring the stiffness centre to the centre of mass.

e) The isolation in bridges can be efficiently and easily employed by changing isolators from thermal expansion bearing However, the expense using the isolators will vary according to the type of the structures. For those structures which are recent, it may cost about 3% of the cost of the construction. Moreover, those structures which need Strengthening may cost relatively less. The base isolation also has a lower environmental cost since the wastage produced during the time of construction is low.

<u>Seismic isolation device</u>

The system of isolations which can be used are in large numbers. It is approximated to 50 or may be more patented isolators which are live worldwide. Elastomeric is the largest family of bearing. The sliding bearing is also becoming a popular choice nowadays.

<u>Elastomeric System</u>

It is noted that the Elastomeric isolation systems are becoming a popular choice nowadays. These systems are rather simple wherein the content is steel plates that are bonded with thin sheets of rubber. The steel plates in the system help to transfer the vertical forces through its provision of stiffness as well as the load capacity in the vertical direction. Moreover, the inclusion of the thin sheet of rubber helps by providing the horizontal flexibility by shearing deformability.

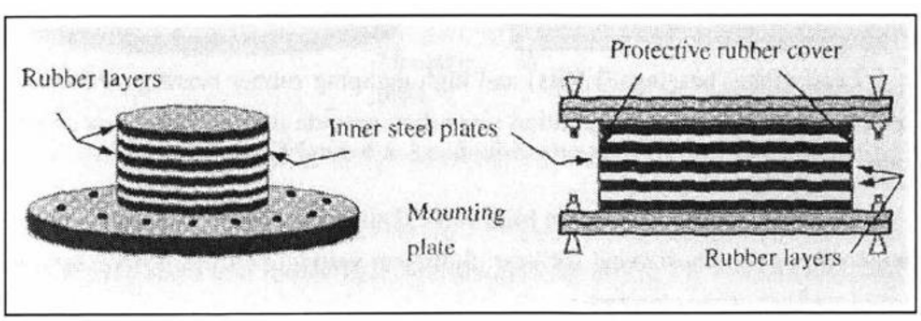

FIGURE 3.38: Schematics of Elastomeric bearing (Techniques of Seismic Strengthening for Concrete Structures)

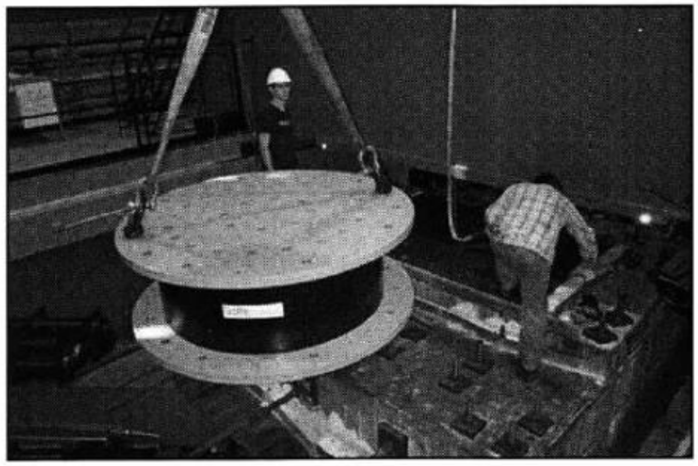

FIGURE 3.39: Elastomeric bearing lab testing (Techniques of Seismic Strengthening for Concrete Structures)

To increase the lateral stiffness of bearing, rubber layers of the system can be added but not the thickness of it individually. It should be noted to prevent the buckling failure so the height to be kept should be half of that of its diameter. 300% deformation without damage is experienced with the use of natural rubber which is a nonlinear viscoelastic material.

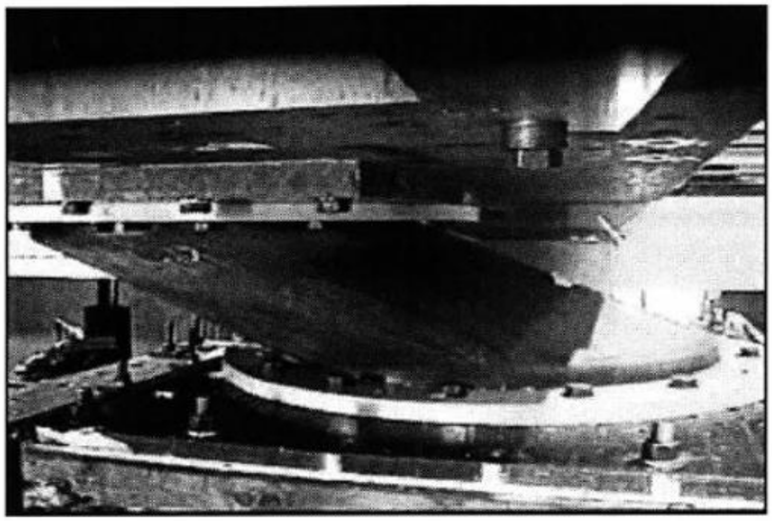

FIGURE 3.40: Elastomeric bearing under deformation testing (Techniques of Seismic Strengthening for Concrete Structures)

Moreover, the rubber has characteristics of rehabilitations force which will help the system to return to its original positions. Even though the initial expense is high the maintenance is relatively low. They are not the most efficient type of isolators due to the fact that they lack the energy dissipation device nor a mechanism that will help the generated minor lateral service load. The bearing intended for the building may be utilized parallel with those other types of systems like a damper. Otherwise, be incorporated with those devices like high damping rubber bearings or it can be lead plug bearing.

Lead Rubber Bearing (LRB)

Lead Rubber Bearing is low-damping thin rubber layers attached to steel plates. These are fitted with a lead cylinder in the centre hole. The functions of the steel and rubber are the same as mentioned in the previous sections. The lead in this bearing gives the rigidity to the structure against the lateral loads which are minor as well as acts as an energy dissipation system.

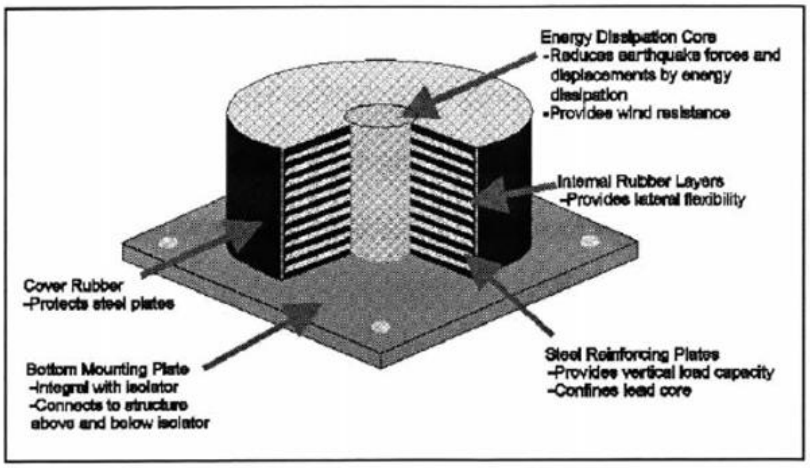

FIGURE 3.41: Schematics Lead rubber bearing (Techniques of Seismic Strengthening for Concrete Structures)

The high initial stiffness is thus provided from the lead plug. Due to the yielding of the plug, there's a dissipation of energy which activates at a low-stress level (at 10.5 MPa)

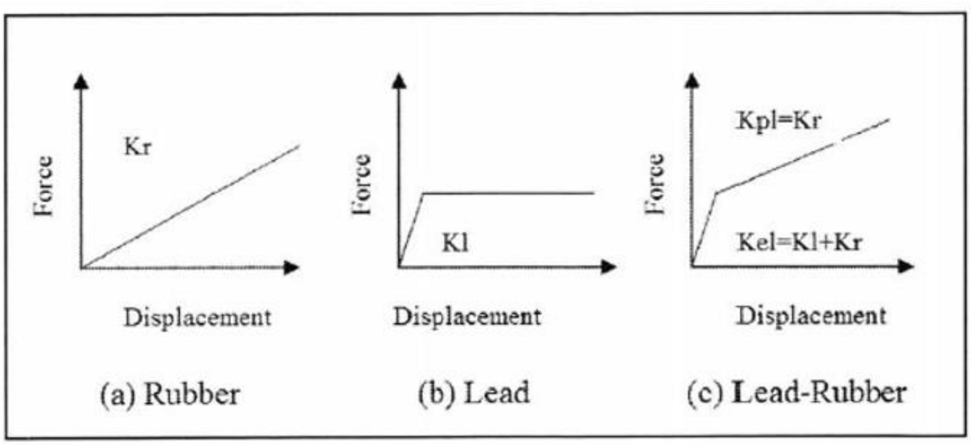

FIGURE 3.42: Mechanical behaviour of Lead rubber bearing LRB (Techniques of Seismic Strengthening for Concrete Structures)

Before the lead yields, there won't be any energy dissipation. As a matter of fact, these particular characteristics possess a problem to the movement-sensitive structures due to the reason where the structure will experience deformation during a micro tremor or minor wind load which is low lateral loads. Hence a system of parallel damping is utilized to resolve this issue.

High-damping rubber bearing (HDRB)

In high damping rubber bearings, the low damping material is replaced with high damping rubber. With the mechanical properties without being affected this high damping rubber is a compound material filler like resin as well as carbon added additionally into the content. Therefore, when the shear is applied dissipation of energy as well as frictional heat is generated due to the sliding molecules within the system interacting with each other. These behaviours are charted with an elliptical hysteresis loop. These are available for strains which are large as well as small in nature. The major benefits of using the high damping rubber bearings are that when at the start of rubber deformation at a very low strain the dissipation energy begins. But HDRB does not have the characteristics of initial stiffness due to which larger displacements are experienced even at smaller loads. Moreover, the temperature severely influences the mechanical as well as the damping properties.

If the two aforementioned systems i.e., high damping rubber bearings (HDRB) and Lead rubber bearings (LRB) are utilized together then the resulting advantages are from both the systems which are low strain dissipation of energy and stiffness. Moreover, using parallel systems can be avoided. There are indeed 2 distinct methods of HDRB & LRB combinations, which are: -

a) By creating a system of high damping rubber layers attached to the steel plates with the inclusion of a lead plug in the centre thus resulting in lead high damping rubber bearing (LHDRB)
b) Creating a combination was in by isolating high damping rubber bearings (HDRB) and Lead rubber bearings (LRB) at the structure level.

Sliding isolation system

The usage of the sliding bearings was practiced since 1993 which also were included in the specifications of the American Association of State Highway and Transportation Officials (AASHTO) This system is based on the friction theory and is made of Teflon as well as stainless steel. For the structures, this system provides stiffness during lateral forces which are low. At a point when the frictional forces are surpassed by the increased lateral forces, movement starts for the system. The major benefit of the Sliding isolation system is that the coefficient of friction is the basic factor at what level the force has to be transferred to a structure. Additionally, this system is seismically independent which makes it effective during a major event as well.

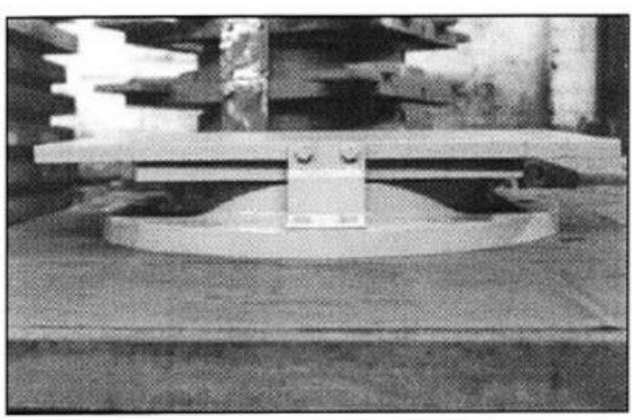

FIGURE 3.43: System of sliding isolation (Techniques of Seismic Strengthening for Concrete Structures)

This system is comparatively not expensive as well as compact in size. It can be utilized when there is a requirement of high pull-out forces. But at the same time, this system has many drawbacks as well which are: -

a) Thermal changes, fatigue as well as deterioration possess an issue to the system.
b) Majorly they do not have any backup system to put them back to the original position. Which is in an event of the first earthquake if the system finished at the non-original position, then during the next earthquake the bearing system will provide lower accommodation which might be lower than required.

However, many solutions are there to overcome these issues which are: -

a) Creating a combining with elastomeric bearings due to its restoring forces which will also be provided to both systems
b) Using a friction pendulum system (FPS). This system has 2 parts which are a slider and then stainless steel with a spherical surface. The surface is placed upside down and thus due to its geometry, the system produces an action of self-centring, during which a specific frequency, as well as stiffness for the entire system, is been provided by its radius of curvature. The friction generated due to sliding elements, energy dissipation is also been provided.

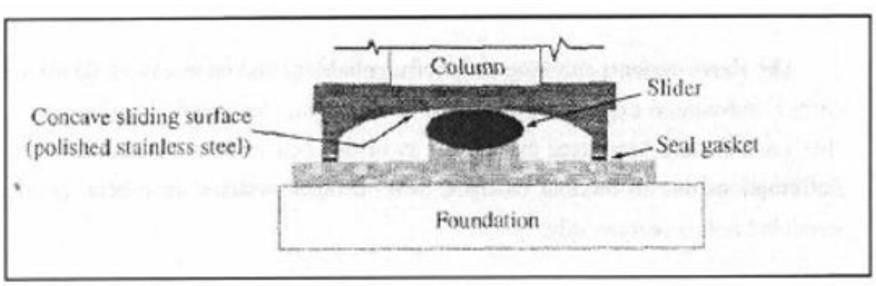

FIGURE 3.44: System of Friction pendulum (Techniques of Seismic Strengthening for Concrete Structures)

Let's take and a bridge structure to know about the method mentioned in general. It was known from a seismic event in 1995 in Japan about the vulnerability faced by the bridge bearings. The numerous failures occurred which did have any clarifications. The displacements due thermal changes have been accommodated by these bearings in the bridges and yet their failures have not been explained. However, a solution was to be chosen to replace and strengthened by isolation bearing. Anyways due to the fact that the replacement was mandatory for the bearings, isolation bearings were utilized since it avoids Strengthening columns and foundations due to its characteristics to reduce the earthquake loads. When using isolation bearings 2 main concerns are to be noted, such as: -

a. The vibrational period is increased which will result in increased displacement. This change has to be accommodated in the retrofit by a longer expansion joint as well as abutment changes.
b. If the isolator bearings are used in a bridge designed to be in soft soil, then it might worsen the situation. That is, if the structure is designed to be flexible already by employing in increased flexibility may bring the natural frequency close enough to the frequency of the earthquake instead of pulling away from it.

CHAPTER 4: REVIEW ON EXTERNAL POST TENSIONING METHOD

4.1 General Concept [4 & 5]:

The method of External Post Tensioning (EPT) can be described through the images below

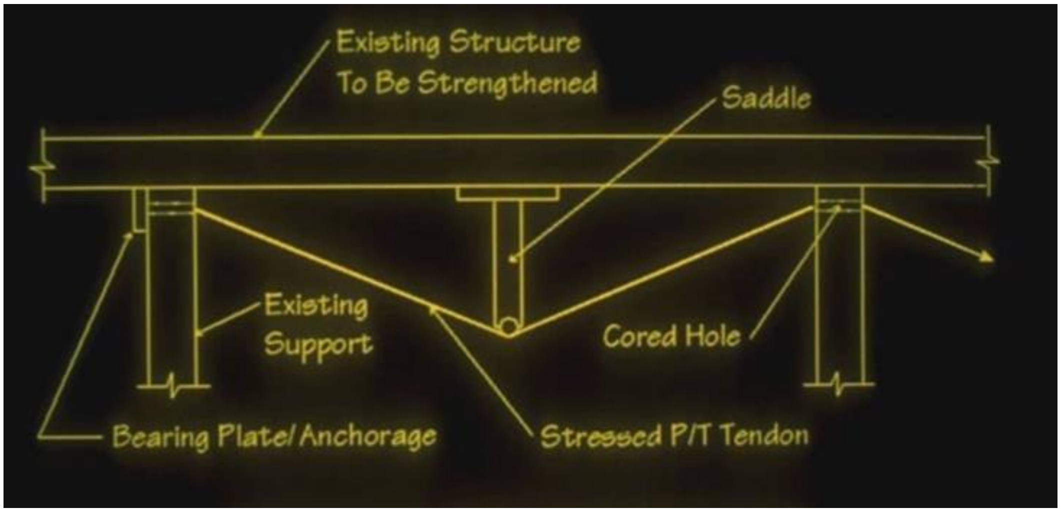

FIGURE 4.1: Schematic of External Post tensioning system EPT (ACI-318, CEU)

The External Post Tensioning (EPT) Strengthening comprises of a King post, lower cord, tension cord of the trusses, Saddle, P/T tendon and the bearing plate/anchorage. The King post/Saddle is the structural steel assemble that exerts an upward load through a saddle also known as a deviator which is made of a structural steel tube profile.

A bearing plate is attached to the existing structure via bolting. It is then welded with a double extra string steel pipes to the bottom of the tubular section under which tendons are passed. The welding is done to prevent from a rolling action.

The existing structure then acts as the compression cord which is the upper chord of the truss. The existing supports (either column or walls) are drilled with holes to fix the anchorages and bearing plates. After the installation of the components of the External Post Tensioning (EPT) system, the steel tendons are then stressed which will make try to straighten the tendons. However, the straightening is prevented due to the structural steel deviator and when the system came to equilibrium, then a very significant amount of upward force is applied to the structure. However, the axial loading of the structure is not affected. The efficacy of an External Post Tensioning (EPT) system is depended on the available amount of sag which is the function of the headroom in an existing structure.

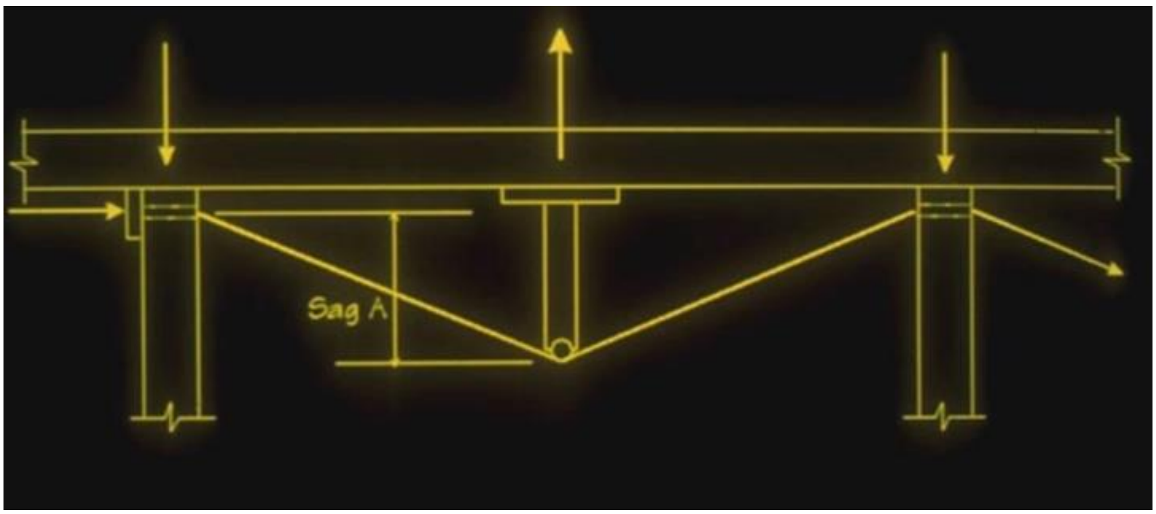

FIGURE 4.2: Schematic of Load application by External Post tensioning system EPT (ACI-318, CEU)

The type of structures which an EPT system can be used also includes one-way slabs where exiting beams are drilled with holes and then build a truss in a convenient spacing. Strengthening of beams and girders typically involves a wrapping a structural steel saddle assembly.

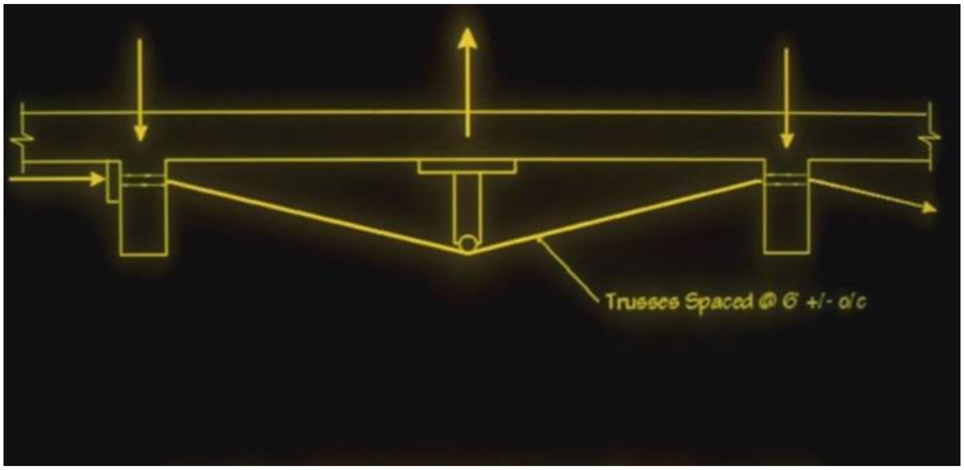

FIGURE 4.3: Schematic of Load application of one-way slab supported on walls or beams (ACI-318, CEU)

If there was no headroom under the existing beam is wrapped relatively thin plate around the soffit of the beam and structural steel tabs on the sides and then would weld the pipe/roller which would then take the upward force from the tendons. At the existing supports the holes are drilled and then insert a double extra strong pipe through which it gave a better bearing when it is dry packed and applied with the tendon force to those tubes / pipes.

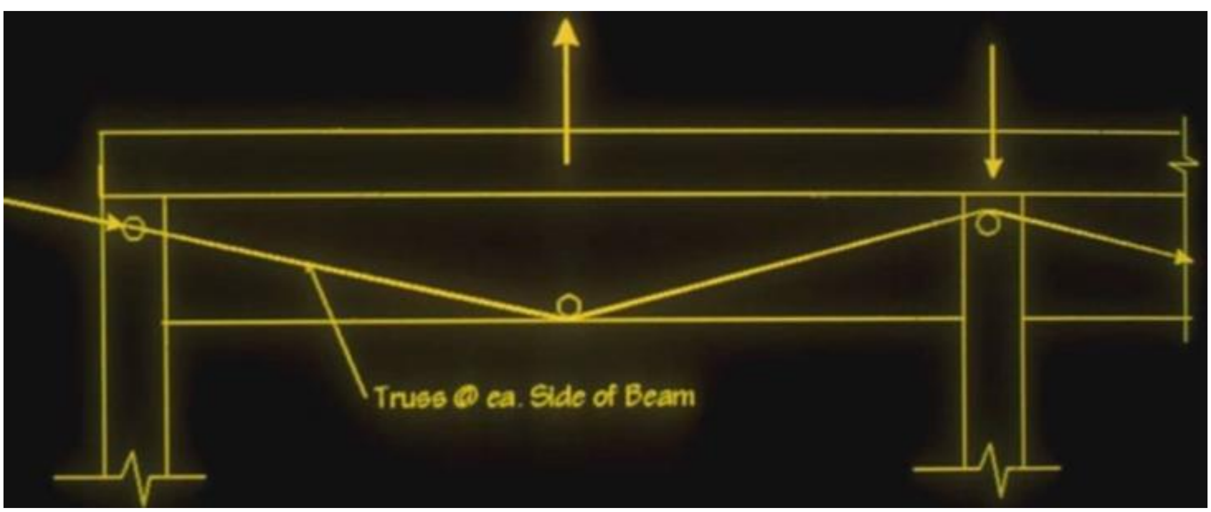

FIGURE 4.4: Schematic of Load application of one-way slab supported on girders or beams (ACI-318, CEU)

In the case of the two-way slabs which had a strength deficiency or an excessive deflection, the application of External Post Tensioning (EPT) will have to be studied and installed. As per a thumb rule the most beneficial place to apply the upward force is in the middle of the plan of the two-way slab which will also be cost effective. Which would relieve the most deflection and most bending. However, it doesn’t relieve most of the shear

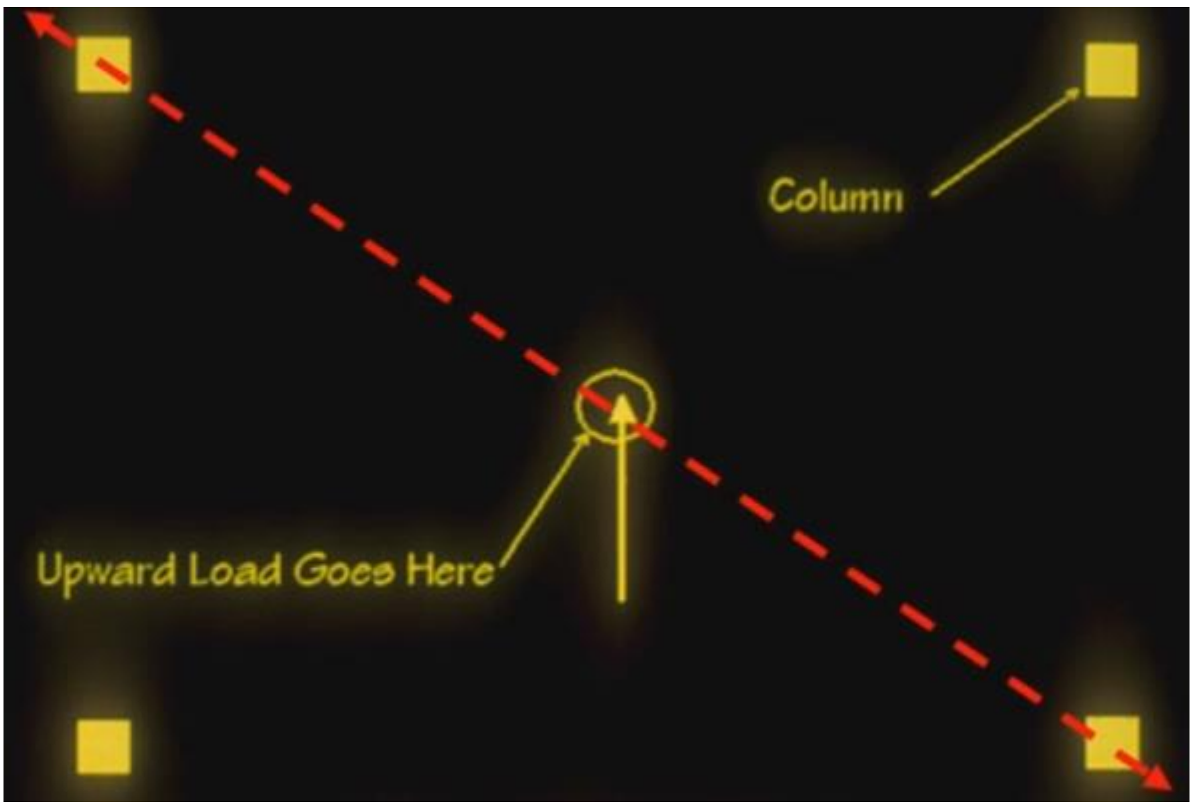

FIGURE 4.5: Schematic of Load application of two-way slab supported on columns (ACI-318, CEU)

The most direct way to apply load would be to install the truss system diagonally between two columns in which the loads are fully carried the two columns which is not practical since most of the column are in square or rectangular shapes which do not comprehend with drilling. Add to it the orientation of the column bars virtually prohibits a clear path through the column. Then there is the problem of placing the bearing plates at the corners as well. A new system of orthogonal trusses has to be implemented to achieve the solution for the two-way slabs. It would apply the upward load at the centre of the slab with a beam truss which ran parallel between the columns. Then the load is carried over to the girder truss which then released the load at another type of saddle which is called as B saddle which had a roller at the top as well as oriented to take the beam truss and another roller at the bottom to take the girder truss which would then carry the load to the columns.

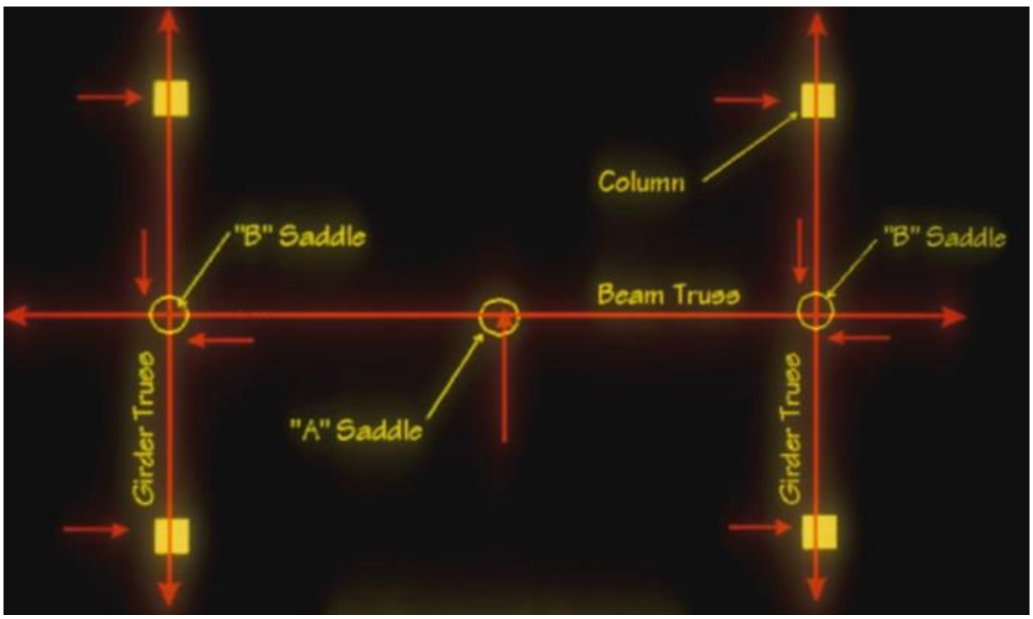

FIGURE 4.6: Schematic of Load application of orthogonal trusses (ACI-318, CEU)

From the below image the A saddle is where the upward load is applied to the centre of the slab and the beam truss which carried the load over to the girder line where it releases the load to the B saddle which has a roller at the bottom that accommodates the girder truss which carried the loads over to the columns. It is to be noted that the upward load is bigger than the downward load which can be hazardous.

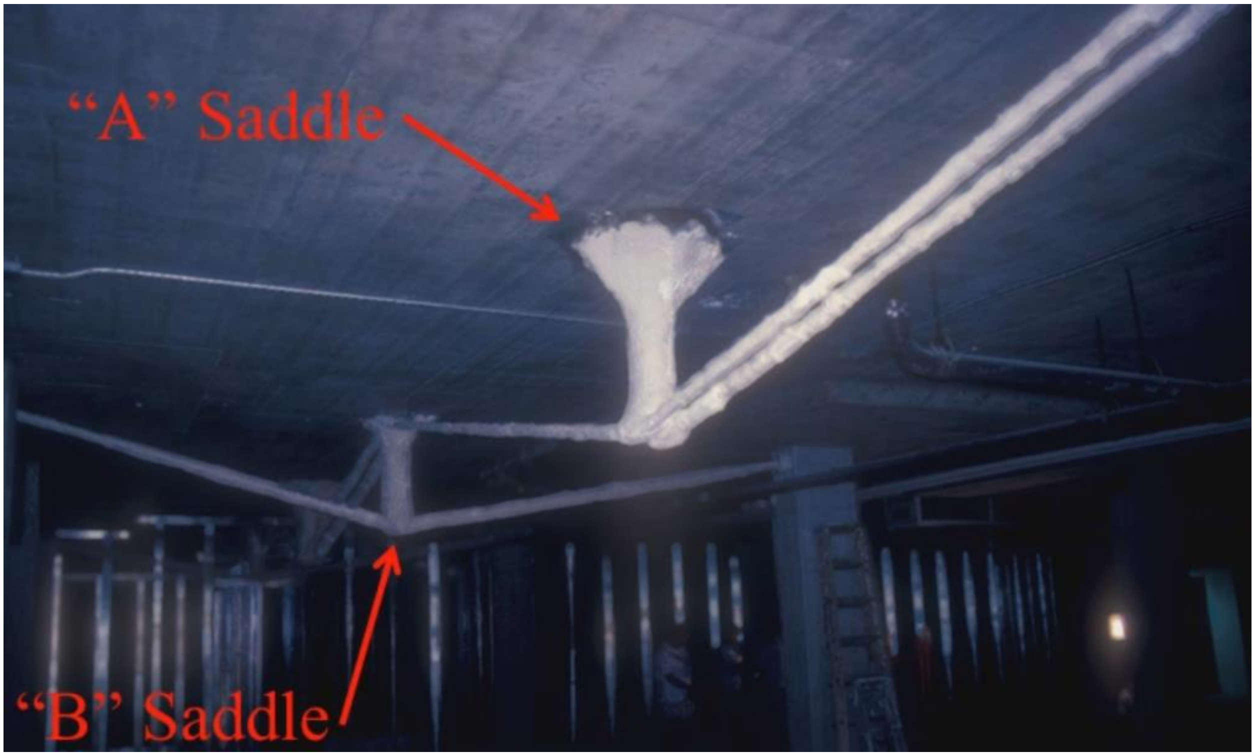

FIGURE 4.7: A & B saddle markings (ACI-318, CEU)

The image shown is 'A' saddle or king post which is used in a one-way slab repair. This assembly got a bearing plate bolted to the slab temporarily to hold the weight. It also has the square hollow steel section tube with a double extra strong which is called a roller with welded tab on the either sides to prevent the strand from sliding/rolling of the roller accidentally.

FIGURE 4.8: King post or A-saddle (ACI-318, CEU)

The 'B' saddle where in the downward reaction from the beam truss is applied at the top of the girder and the girder truss which carries the load to the column is at the bottom.

FIGURE 4.9: King post or B-saddle (ACI-318, CEU)

The following image is a typical example of a one-way slab strengthening.

FIGURE 4.10: One way slab strengthening (ACI-318, CEU)

The following image is a typical example of a two-way slab strengthening.

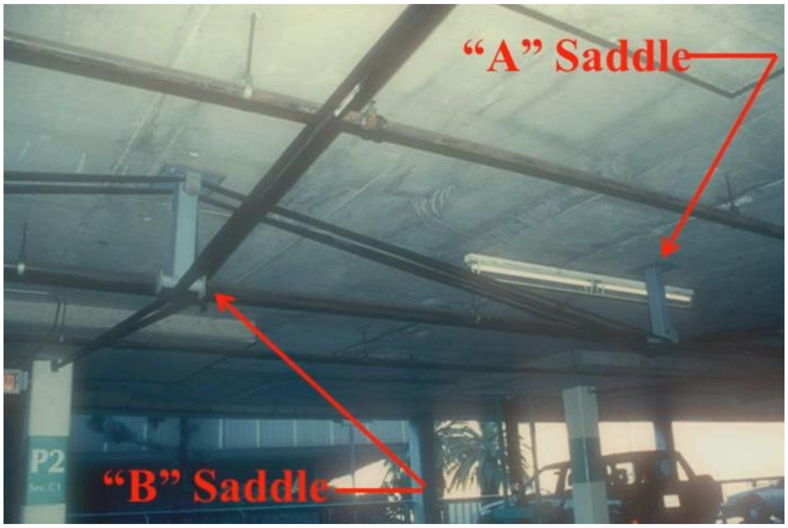

FIGURE 4.11: Two-way slab strengthening - orthogonal (ACI-318, CEU)

The girder shown in the image is to be strengthened. The headroom below the girder was good enough. The holes for the tendons are directly drilled at an angle. The king post is built under the girder instead of alongside.

FIGURE 4.12: Strengthening of girders and one-way slabs (ACI-318, CEU)

Fire Proofing

The fire proofing of the External Post Tensioned tendons is very important since it provided a substantial portion of the capacity of the structure which is existing. There a regular types of fire proofing like fire proofing spray on, encasing the tendons in a drywall but these showed to less effective. However, the use of cell furring metal lath which wrapped around the tendons as well as the structural steel components. A vermiculite plaster is then applied to it as shown in the image. These techniques is in coherent with the International Building Code (IBC) TABLE 720.1(1).-1.6.2- Steel columns and Primary trusses i.e.; 'application of perlite or vermiculite gypsum plaster over self-furring metal lath wrapped directly around the column'

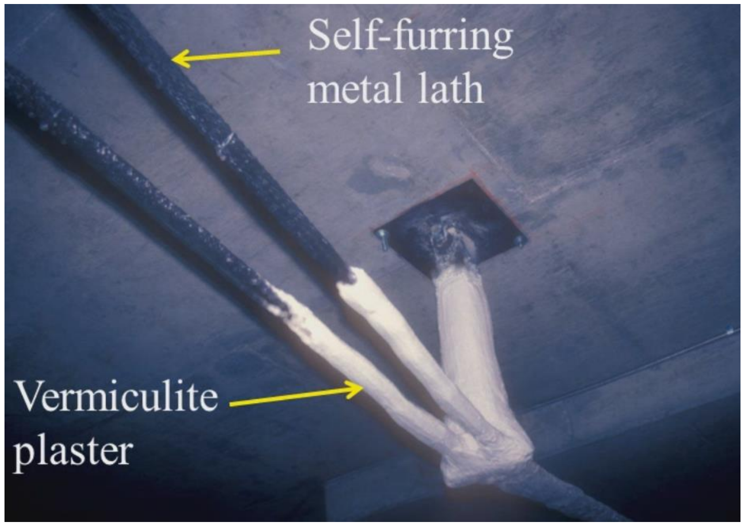

FIGURE 4.13: Fireproofing technique (ACI-318, CEU)

The code requires to follow a minimum thickness for 2 hours the recommendation is 2.54cm thickness, for 3 hours the recommendation is 3.5cm thickness and for 4 hours the recommendation is 4.5cm thickness. However, a 5cm cover is highly suggested to get at least a 5-hour rating for conservatism.

The plaster can be moulded to achieve an aesthetic shape as shown in the below image. The building in the image suffered extremely from the punching shear from the earthquake. Moreover, the engineering design of building did not satisfy the codes. However, the EPT system showed in this image where the upward loads are not applied in the middle but on the column line to maximize the amount of shear that was being relieved.

4.2 Advantages and Disadvantages of the EPT Technique [9]

The External Post Tensioning (EPT) method allows to enhance the structural member to take a large force at any point of location needed. The main purpose of implementing the External Post Tensioning (EPT) method for the bending strength to increase and the other perks are shear strength increase as well as the further deflection are controlled. Hence most of the buildings which are to be demolished due to the failure of its structural integrity, it can be saved using the External Post Tensioning (EPT) method.

External Post Tensioning (EPT) method is minimal, weightless and do not disrupt the function / services of the building to be fixed. It is relatively economical compared to other repair or Strengthening methods as well as it is time saving. External Post Tensioning (EPT) is flexible compared to other methods.

The advantages of using the External Post Tensioning (EPT) for strengthening are in a wide range, to enlist a few are that it is been primarily used as a technique which can be applied to a very large load virtually at any point in the intended structure with a minimal need of headroom because the system of External Post Tensioning (EPT) uses a high strength steel which is substantially weightless. Moreover, the External Post Tensioning (EPT) system has no much impact on an existing column footing or the seismic system.

It can be adjusted to avoid clashing with the existing mechanical systems, plumbing systems as well as HVAC systems. It does not require need any modification to be done to the existing structure to be installed. Yet another added advantage is that External Post Tensioning (EPT) system can be installed without interfering in the functionality of the building and its occupants and the building does not have to be shut down to fix the external tendon. However, this type Strengthening may have to secure the premises rarely but only for a couple of hours.

The disadvantages of an External Post Tensioning (EPT) system are that it’s totally dependent on an existing condition of the structure. If the concrete quality of the structure is suspected to be of poor quality, then the post tensioning should be worked with extreme care and monitored so the structure itself can take the increased stress.

In some structures like bridges the installation of certain components like anchorages or deviators can prove difficult. Moreover, the detailing should be done enough to account for the stress concentration which was already existing in the structure. Another issue of the system is to determine the shear capacity of the beams along with the external tendons. Due to access difficulties the method is often limited to flexural strengthening.

In many cases drilling or welding is a requirement which can be an issue if the structure is at lower strength. Moreover, local stiffeners are added to the system as per requirement. The tendons used in the system is prone to corrosion. These elements are also susceptible to other sources of contaminations, accidental damages like impact or fire or even vandalisms.

A decreased headroom for the installation of external port tensioning method (EPT) is yet another critical disadvantage, strengthening of a railway bridge can be quoted as one of these difficulties as example. Moreover, installation is also proven to be difficult in certain conditions as well as confined spaces.

4.3 Types of Structures Preferred and Installation Methods for EPT [13]

In those cases, with a single strand that have a 1.27cm diameter it is greased and wrapped if only one or two strands are needed to achieve the EPT system then the hole is done with a Roto-Hammer. For the cases were the system needs a 5-10 cm diameter holes then a regular core drilling equipment with diamond bits are used.

FIGURE 4.14: Coring using Roto-hammer technique (ACI-318, CEU)

FIGURE 4.15: Coring using special equipment for larger holes (ACI-318, CEU)

The tendons are stressed with a conventional stress equipment as shown in the image.

FIGURE 4.16: Stressing of tendons (ACI-318, CEU)

For those buildings where interior stressing in required then a double extra strong steel pipe is used then the strands are overlapped like in the image shown at the centre of the structure and stresses each strand in the required direction. This is one of the effective methods allowing to stress all tendons from the inside of a structure.

FIGURE 4.17: Method of centre stressing (ACI-318, CEU)

4.4 Overview of EPT with an Example [15]

The orange county hall of administration is a building which is the centre of government severely affected by the earthquake. It is in the Southern California in the United States. The building contained an offices and meeting rooms as well as other default rooms. In this building the columns are inclined outwards which would allow to increase the area of the floors as the height increases. The building was built in the 1980 after which it experienced a moderate seismic event at 5.0.

FIGURE 4.18: Orange county hall of administration (ACI-318, CEU)

The use of external tendons did not involve applying the loads in the upward direction but it was applied in the horizontal direction. The building was severely affected by the earthquake. After the investigation it was found to have an engineering mistake which is the horizontal tension load that is required or exerted into the floor system which would prevent the columns from outward rotation was not taken into consideration. However only the eccentricity of vertical load in the columns where only calculated.

It was noticed that every exterior column had a line of circular cracks which formed around the floor slab which depicted that these columns are trying to detach. The External Post Tensioning

(EPT) was planned to simply run the horizontal tendon across the entire building from column to column and tying it together. The project to solve the problem involved six strands of tendons which needed to withstand 667kN of force with a thick steel bearing plate which was placed in the exterior of each column. The holes were milled into the bearing plate because it the holes needed to be tapered. These plates where then architecturally covered.

FIGURE 4.19: Anchor bearing plates for tendons (ACI-318, CEU)

CHAPTER 5: CASE STUDY ON THE EXTERNAL POST TENSIONING METHOD

5.1 Case Study [29]

5.1.1 Agenda:

The information on the External post tensioning method is very limited till the date where there are no optimized or specific guidelines to use the technique of this method of strengthening the structures. The objective about this case study is to bring about the insight on how the EPT method is used as means to strengthen a bridge in Indonesia which was found to be under performing and under strength as well as how the procedure of EPT can be applied to an existing structure. The case study is centred on the researches initiated by the Institute of Road Engineering (IRE), Indonesia and the Transport Research Laboratory (TRL), UK.

5.1.2 Introduction:

One of the methods for rehabilitating or strengthen to an existing structure – bridges is the technique of external post tensioning (EPT) which have been in practice in many countries over many years due to its efficiency and moreover the economic solution for a wide range of the conditions as well as the types of bridges in need. The method of external post tensioning (EPT) is growing popular because of the installation speed and the disruption caused for the flow of traffic is relatively minimal compared to the other modes of strengthen the structures and it is the critical factor while choosing the type of strengthen of the structure.

The Condet Bridge located in Indonesia between Jakarta and Citarum is built in 1989 and was designed for a full extension of the highway loading as per Indonesia. However, after few years' service strengthen was a requirement, the bridge which was found to be under-strength due to the increase in heavy traffic. The external post tensioning method was choosing to overcome the situation This composite bridge has a 4-lane road which has a capacity up to 30,000 motor vehicles in a day with over large proportion of heavy trucks. The bridge is estimated to have 3 spans which are 24m, 48m and 24m as show in the following image. The case study here in is fraction of the continuing project carried out by the IRE & TRL on the strengthening of bridges which is being funded and will have an end results in creating a specific guideline to work the method of external post tensioning method for the bridge strengthen. External Post Tensioning (EPT) method is chosen for the bridge since it proved to minimal cost on the economic grounds as well as it causes minimal disruption to the flow of traffic conditions. Moreover, it has components which low weight with lower time of installation. Additionally, the future operations can be worked out quickly with much more convenience.

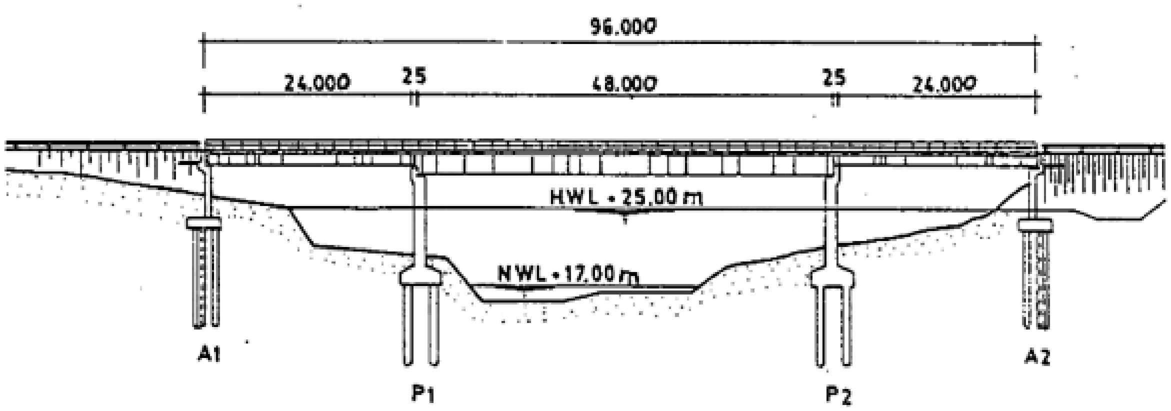

FIGURE 5.1: Bridge Elevation

5.1.3 Brief:

The demand of transportation system for faster and more efficient is always rising with its weight / capacity of the traffic throughout the world. Moreover, the overloading of vehicles beyond the legal vehicle loading is a common problem which has to be accounted for while designing the bridges as well.

The measure taken to solve the increased flow of traffic, widening of the bridges often the measure to increase the road network's capacity which led to these bridges carrying significantly greater loads than the loads they were originally designed to carry. Such issues are often encountered in developing countries like Indonesia due to the accelerating development of the country. Over majority of the areas the road network system is only way of transporting people, goods and other vital items needed for the whole region

The minor roads which were originally designed to capacitate light traffic are now used to transport the modern heavy loaded motor vehicles. Moreover, these roads also being upgraded significantly to cope with the ever-increasing demands. There other reasons leading to under strength of a bridge even though it was engineered for appropriate loading specifications such climatic effects, rusting, impacts and so on.

Those bridges which were designed as per the earlier code specification of loads are now obsolete to carry the modern heavy good vehicles. This problem also likely to affect those bridges which have suffered deterioration or damages. Such situations will result in for the choice of rehabilitation or restricting the traffic by the bridge owners / managers.

Along with this issue in the competition for the funds to keep up the infrastructure leads to a pressure demanding for the bridges to be kept in service, capital minimalizing as well as expenditure of its maintenance. However, the strengthening of the bridge is always a better choice of option over the complete replacement of the structure which would provide an effective economic solution considering the situations being appropriate. It should be noted that the traffic management expense can reduced drastically in cases where the rehabilitation or strengthen is planned to avoid a complete closure of the road.

5.1.4 Observations:

A number of factors depends on the selection of the type method chosen to strengthen a structure. Moreover, this parameter extends to the structure type, the requirement of the strength needed to be increased as well as the costs which results in doing so. There many methods of strengthen the structures but they also have limits of how flexible they can be to achieve the desired strength to be increased.

It is quite evident that strengthening a structure would cost much lower than a complete replacement, but the method chosen for strengthen would need to be justified on the economic factors. It is to be noted that while selecting the method for strengthening the maintenance cost associated also has to be captured over the initial capital costs with the future services. Also, the pre-existing condition of the bridge is an important factor. In some cases, these factors may limit the advantage of certain techniques of the strengthening.

The design of the bridge was originally comprised of a pre-compressed deck with each span having ten steel beams as well as in-situ reinforced concrete slab. As shown in the following image the casting of slab into two segments with a space at the mid span.

These segments were joined with at the support of the beams with those reinforcement acting as an anchor. During the segments were casted, the flat jacks were carefully inserted into those gaps which was left at the mid spans. Then force was applied which resulted in the concrete compression and hogging the moments in the steel beams.

The space with flat-jacks were filled with plug of high strength concrete to keep the pre-compression. Shear connectors were used along the beam were not bonded with the concrete while casting due to the use of void formers were grouted to complete the action of composition.

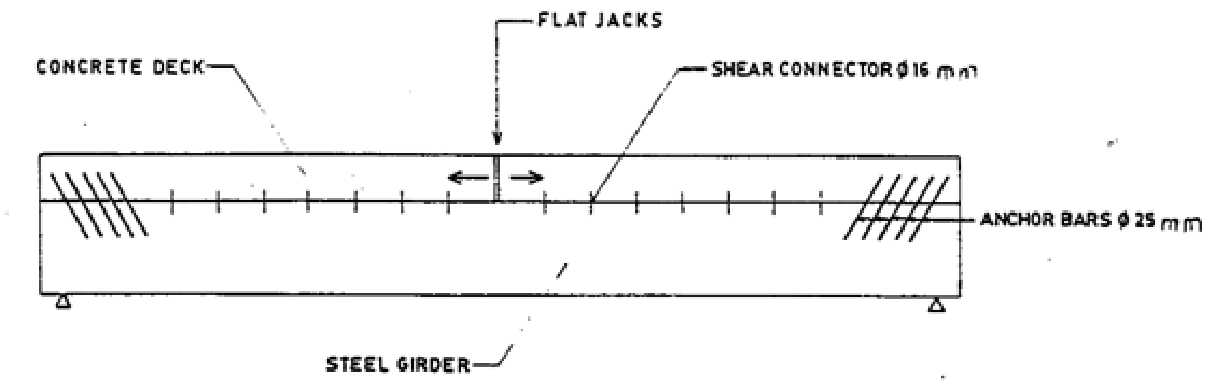

FIGURE 5.2: Pre-compression Method

5.1.5 Investigation:

Openings / gaps were found in the joints which were located in between the concrete plugs as well as the in-situ RCC slabs after the service of five years. After the investigation of the bridge deck showed a permanent deflection at 65mm, 115mm & 78mm over the three different spans discussed earlier respectively. Moreover, the vibrations produced by the traffic also was causing inconvenience for the pedestrians as well as the drivers using the bridge. The behaviour of the deck was determined through a load test under vehicle loading. The mid-spans were equipped with strain gauges at three composite sections so as to analyses distribution of stress. The leading results showed that the composite nature intended for the bridge was dysfunctional due to the separation of neutral axes in the steel sections as well as the concrete sections. It was evident that the maintenance of pre-compression wasn’t captured in the deck. This led to creep as well as the shrinkage of the concrete slab due to which the capacity of the bridge was calculated to have a 35% reduction.

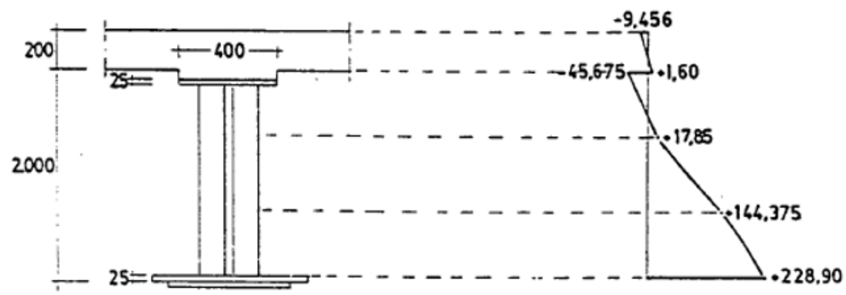

FIGURE 5.3: Stress Distribution before the method of strengthening (kg/m^2)

5.1.6 Methodology:

The methodology used for strengthen of the Condet Bridge are centred to research projects by the TRL and IRE which are: -

- The bridge deck being subjected to re-compression through the use of re-installed flat jacks and by the replacement of the concrete plugs.
- The steel beams were installed with the steel trusses underneath.
- The use of external tendons for deck stiffening and thus to replace the pre-stress forces.

The following figure is a schematic of the strengthen layout planned for the three different spans of the bridge. Two steel cables of 12.7mm high strength 3 strands were used for each beam maintaining 2m eccentricity at the third of the middle of span. Each wire of 7 strands were greased as well as polyethylene tubes were used to sheath these strands to prevent from corrosion.

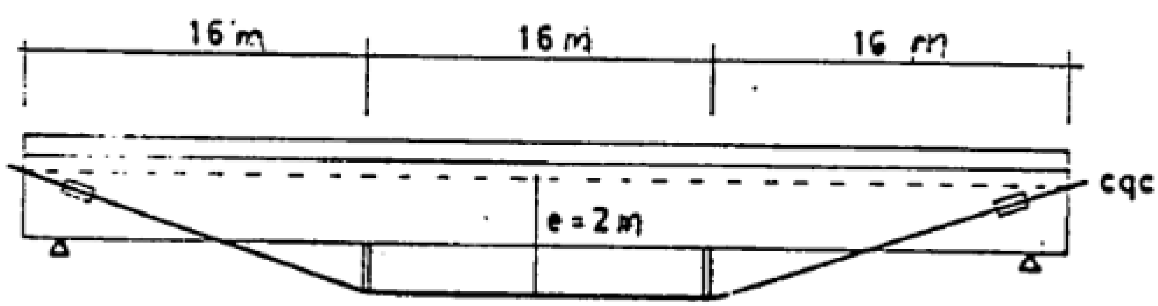

FIGURE 5.4: Cable arrangement layout

A special custom-made anchor plates were used to fix / anchor the tendons which was located near to the supports. The following image shows the detailed geometry of the anchor plates which are 20mm in thickness. A standard VSL barrels as well as wedges were used in anchoring of strands. These anchor plates were then welded with incorporation of 9 x 16mm dia bolts as shown in the image. At the points of anchorage, the provided sheathing for strands were removed enough to accommodate the stressing as well as wedges equipment installations.

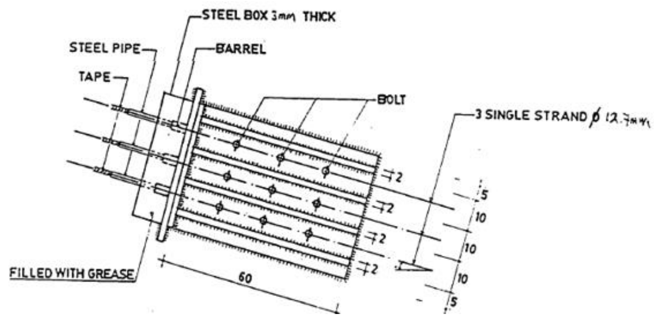

FIGURE 5.5: Anchorage arrangement layout

To fully protect the anchorages from corrosion a steel box was made to fabricate after the process of stressing where the wedges as well as barrels were enclosed fully which was then filled up with grease. Those areas where the strands were protruding out from the box, it was covered with grease filled pipes. All other exposed areas were then covered by greased tape to achieve the complete seal of the system. Standard I beam were used in the production of deviators as shown in the image. A steel pipe of 50mm diameter were used to group three strands passing through to achieve the deviation which was then welded over to supporting elements. The tendon was protected further by placing polyethylene pipe in the deviator and sheath was made continuous. Cover plates of 15mm thickness were used underneath of the steel beam's top flange for 1.6m in length to provide enough local strengthening which was located at deviator. Moreover, stiffeners were also included in the location of the deviators for the prevention of the high stress concentrations as well as the local buckling.

The following image is the Condet Bridge's underneath after the procedure of strengthening. The layout for each side spans were followed with a similar design as well. The cables tensioning procedures were worked in stages so as to prevent longitudinal cracking of the concrete deck due to the beam's excessive differential movements. 13.1 tons of force were used as design pre-stress force in each strand which was applied in four stages with the use of hydraulic jack with a capability of light single strand. During the stressing of the cables the bridge was under monitoring to detect if any overstressing or damage was made. After the complete installation the mid span of the deck moved vertically upwards about 52mm.

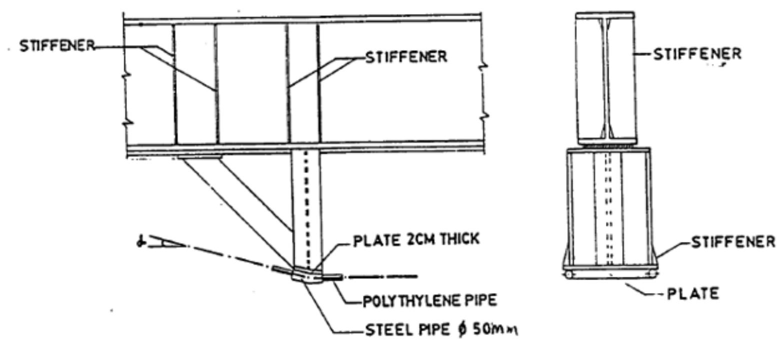

FIGURE 5.6: Deviator arrangement layout

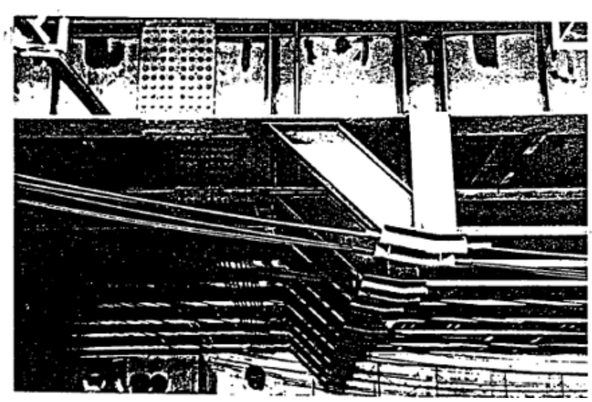

FIGURE 5.7: Underside strengthening arrangement layout

5.1.7 Precautions:

The strengthening steel stresses installation under the deck can be planned at an economical cost with no major closures is required for the bridge. However, during the erection of these trussed would-be time consuming along with extensive scaffolding as well as other temporary structures under the bridge in the river adding a significant amount of dead weight to the deck thus imposing many risks involved in the work. Therefore, safety measures have to be followed closely.

5.1.8 Conclusions:

The development of the methods chosen to strengthen a structure for modern constraints is required to be effective at the same time economical, particularly those techniques which causes little disruption on the flow of traffic and road closures. These methods have to be inexpensive as well as easy to install to attain such goals. Thus, External post tensioning method was chosen and was a preferred technique to be used for strengthening. Additionally, the future operation on the assembly would be quicker and convenient.

The inspection done for the bridge revealed that the functionality after the EPT installation seems to be in good condition. However, there was flood strike on the assembly in 1995 were all the tendons got submerged which was unexpected and unaccounted for in the design stage. No further detailed inspections were carried out to check for corrosions or any other damages caused. However, all the elements such as tendons, deviators as well as the anchors showed to have satisfactory condition through visual inspections.

This method is used extensively by many countries over decades due to its easy installation and the minimal amount of capital cost. However, no guidelines have been implemented to provide the engineers with an accurate design. This case study set an agenda for the engineers to come about basic guidelines to achieve for similar structures like bridges.

CHAPTER 6: CONCLUSION

6.1 Conclusion of Research

- The low rigidity of the RCC structural members at the ground floor level is one of the main factors that cause the soft-story collapse. The ground floor rigidity becomes lower compared to the upper stories if there is no inclusion of the infill wall. Hence this leads to the failure of the structure during an earthquake. This failure mechanism can be avoided if special attention is put into during the design phase with the inclusion of more details.
- Lack of transverse reinforcements, as well as an absence of the hook bending of the ties in structural elements, results in damages. This issue can be overcome by utilizing the close-spaced stirrups as well as betting hooks to enhance the shear resistance of a structural element.
- The short columns fail often when it has partially filled infill walls in the system of RCC frames. The shear strength should be increased of that specific part of the column to avoid the failures.
- A hammer effect is experienced due to different natural vibration periods just after the first wave of the shake during a seismic event. Hence relevant distance/gap between the structures should be maintained as per the latest codes to avoid such an issue
- A failure mechanism for weak column-strong beam if rigid and deep beams are been utilized with a column which is flexible. To prevent such an issue is that the sum of moments at the column joint should be effectively larger than that of the total moments from the beam at the same joint.

- The lateral stiffness decreases if the workmanship is bad, the concrete used is of low strength, and the steel bars utilized are corroded. Inspection of the workmanship, as well as the concrete, can help to eliminate such problems in the construction.
- The low strength of the materials in an infill compared to that of the RCC frame will result in the failure of gabble walls, in and out of planes. Hence to refrain from such catastrophes an adequate efficient connection has to be maintained. Moreover, mortar used should be high strength b/w the RCC frame and the wall.
- External post tensioning (EPT) is a powerful method to strengthen an existing building affected by a seismic damage. This has been a remedy to engineering design errors where it can increase the flexure and the shear strength. This also has been used for occupancy changes and increase the live load. It also can be used as a repair to buildings which have been damaged by corrosion as well. Moreover, the system is weightless and involves no disruption to an existing facility as well as it can executed while the building remains operational. It is found to be economical as well.

6.2 Scope for Future Research

Many structures which have been build will always require strengthening after it's found under performing hence many applications have been implemented to achieve the required level of strengthening. Due to such requirement in the past decade the use of External Post Tensioning Method have been used which revolutionized the technology of strengthening until it's been considered as the most cost effective, efficient as well as durable choice. With ever increasing developments in the structural analysis, the use EPT method have also been relatively simple to install and construct till this date. The method of EPT provides the user with a wider range of possible solutions for steel, concrete and timber structures. Like in every other method of strengthening the EPT method also needs to have an initial investigation over the structure intended. However, it is to be noted that the EPT method will maintain the level of balance between the constructability as well as the engineering design. Furthermore, the use of the EPT is still in research and possibilities of using while considering the cost will prove to more flexible and viable solution to the construction industry as such.

REFERENCES

[1]. Oliveto, G. & Marletta, M. (2005). Seismic Retrofitting of Reinforced Concrete Buildings Using Traditional and Innovative Techniques. *Iset Journal of Earthquake Technology*, Vol. 42(454), Pp. 21–46.

[2]. Petrovic, D. B. B., Manakou, S. K. M., Raptakis, T. B. D. & Parolai, K. D. P. S. (2015). Seismic Response of an 8-Story RC-Building from Ambient Vibration Analysis. *Bulletin of Earthquake Engineering*. Springer Netherlands, Pp. 2095–2120.

[3]. Promis, G., Gabor, A. & Hamelin, P. (2012). Effect of Post-Tensioning on The Bending Behaviour of Mineral Matrix Composite Beams. *Construction and Building Materials*. Elsevier Ltd, Vol. 34, Pp. 442–450.

[4]. Ranganadhan, A. & Paul, A. (2015). Seismic Retrofitting of An Existing Structure. *International Journal of Research in Engineering and Technology*, Pp. 42–46.

[5]. Recupero, A., Spinella, N., Colajanni, P. & Scilipoti, C. D. (2014). Increasing the Capacity of Existing Bridges by Using Unbonded Prestressing Technology: A Case Study. *Hindawi Publishing Corporation Advances in Civil Engineering*, Vol. 2014.

[6]. Saatcioglu, M., Asce, M. & Yalcin, C. (2003). External Prestressing Concrete Columns for Improved Seismic Shear Resistance. *Journal of Structural Engineering Asce*, (August), Pp. 1057–1071.

[7]. Safety Requirements for The Structures in An Earthquake Prone Zone. (2016). *E-Issn No: 2454-9916* |, (March), Pp. 66–67.

[8]. Sahin, C. (2014). Pdxscholar Seismic Retrofitting of Existing Structures. *Pdxscholar*.

[9]. Soltanzadeh, G., Osman, H. Bin, Vafaei, M. & Vahed, Y. K. (2018). Through External Post-Tensioning. *Bulletin of Earthquake Engineering*. Springer Netherlands, Vol. 16(3), Pp. 1487–1510.

[10]. Todisco, L., Stocks, E. & Leo, J. (2018). Enhancing the Structural Performance of Masonry Structures by Post-Tensioning. *Nexus Network Journal*, Pp. 671–691.

[11]. Yön, B., Sayın, E. & Onat, O. (2017). Earthquakes and Structural Damages Earthquakes Damages. *Creative Commons Attribution*.

[12]. Zhai, C., Zheng, Z., Li, S. & Pan, X. (2017). Damage Accumulation of a Base-Isolated RCC Building Under Mainshock-Aftershock Seismic Sequences. *Ksce Journal of Civil Engineering*, Vol. 21, Pp. 364–377.

[13]. Barchas, K. J. (1991). Repair and Retrofit Using External Post-Tensioning. *The Aberdeen*

Group.

[14]. Caliò, I. & Marletta, M. (205ad). Chapter 16 Seismic Performance of a Reinforced Concrete Building Not Designed to Withstand Earthquake Loading. *Wit Transactions on State of The Art in Science and Engineering*, Vol. 8.

[15]. Centre, O. & Kingdom, U. (1997). Title: Strengthening of Bridges Using External Post-Tensioning. *Transportation Research Record: Journal of The Transportation Research Board*.

[16]. Connor, J. J. (2003). Techniques of Seismic Retrofitting for Concrete. *Bs In Civil and Environmental Engineering Tufts University*.

[17]. Edition, S. & Duggal, S. K. (2013). *Earthquake - Resistant Design of Structures*.

[18]. El-Betar, S. A. (2015). Seismic Performance of Existing R. C. Framed Buildings. *Hbrc Journal*.

[19]. El-Zohairy, A., Alsharari, F. & Salim, H. (2020). Analytical Model and Parametric Study for Externally Post-Tensioned Reinforced Concrete-Steel Composite Beams. *Structures*. Elsevier, Vol. 27(May), Pp. 411–423.

[20]. Emergency, F. & Agency, M. (1997). Nehrp Guidelines for The. *Fema 273*, (October).

[21]. Fotopoulou, K. D. P. S. T. K. S. D. (2014). Consideration of Aging and Ssi Effects on Seismic Vulnerability Assessment of RC Buildings. *Springer Science+Business Media Dordrecht 2013*, Pp. 1755–1776.

[22]. Ghosh, R. & Debbarma, R. (2017). Performance Evaluation of Setback Buildings with Open Ground Storey on Plain and Sloping Ground Under Earthquake Loadings and Mitigation of Failure. *International Journal of Advanced Structural Engineering*. Springer Berlin Heidelberg, Vol. 9(2), Pp. 97–110.

[23]. Gupta, K., Kumar, A. & Khan, M. A. (2017). Review Paper on Seismic Retrofitting of Structures. *Irjet*, Pp. 1981–1985.

[24]. Hauksson, E. (1994). The Magnitude 6. 7 Northridge, California, Earthquake of 17 January 1994. *Science Vol266*, (October).

[25]. Kisan, M., Sangathan, S., Nehru, J. & Pitroda, S. G. (1984). Is 1893-1984. *Is 1893-1984*.

[26]. Lee, K. (2017). Structural Responses of External Post-Tensioned Tendons to Increasing Localized Damage. *Aci Structural Journal*, (114).

[27]. Marletta, M. & Caliò, I. (2004). Seismic Resistance of a Reinforced Concrete Building Before and After Retrofitting Part I: The Existing Building. *Structures Under Shock and Impact Viii*.

[28]. Nienhuys, S. (2019). Reinforced Concrete Construction Failures Exposed by Earthquakes

and Other. *Sjoerd Nienhuys*, (January), Pp. 1–27.

[29]. A F DALY AND W WITARNAWAN (1997) Strengthening of bridges using external post tensioning. *EASTS '97, Seoul*, 29-31 (October) 1997

[30]. Ranganadhan & Paul 2015; El-Betar 2015; Safety Requirements for The Structures in An Earthquake Prone Zone 2016; Ghosh & Debbarma 2017; Gupta, Kumar & Khan 2017; Lee 2017; Yön, Sayın & Onat 2017; Zhai Et Al. 2017; Soltanzadeh Et Al. 2018; Todisco, Stocks & Leo 2018; Nienhuys 2019; El-Zohairy, Alsharari & Salim 2020)