STRENGTHENING OF REINFORCED CONCRETE FRAMES BY USING STEEL BRACINGS

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ABSTRACT

STRENGTHENING OF REINFORCED CONCRETE FRAMES BY USING STEEL BRACINGS

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Structures in high seismic risk areas may be susceptible to severe damage in a major earthquake. Structures designed to meet older code requirements may be at even greater risk. When these structures are evaluated with respect to current code criteria, it is observed that they lack of lateral strength and/or ductility. Since safety and economic considerations are major problems, these structures become viable candidates for retrofit and seismic strengthening.

For the variety of structures and possible deficiencies that arise, several retrofitting techniques can be considered. Diagonal bracing system is one of the retrofitting techniques and it provides an excellent approach for strengthening and stiffening existing building for lateral forces. Also, another potential advantage of this system is the comparatively small increase in mass associated with the retrofitting scheme since this is a great problem for several retrofitting techniques.

In this study, the use of steel bracing for the strengthening of low, intermediate, and relatively high rise reinforced concrete frames are investigated analytically. The ultimate lateral load capacities of the strengthened frames are determined by a load controlled push-over analysis. The post-tensioning effect of preloading is also investigated.

Keywords: Strengthening, Retrofitting, Reinforced Concrete Frame, Steel Bracing, Preloading

ÖZ

BETONARME ÇERÇEVELERİN ÇELİK ÇAPRAZLAR KULLANILARAK GÜÇLENDİRİLMESİ

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Sismik riskin yüksek olduğu bölgelerdeki yapılar büyük bir deprem altında ciddi hasara maruz kalabilir. Eski standartların gereksinimlerine göre tasarlanmış bulunan yapılar bile büyük risk altında olabilir. Bu yapılar mevcut standart kriterleriyle değerlendirildiği zaman, yatay dayanım ve süneklik yönünden zayıf oldukları gözlenir. Güvenlik ve ekonomik koşullar önemli sorunlar olduğu için, bu yapılar iyileştirme ve sismik güçlendirme için uygun adaylardır.

Yapıların çeşitliliği ve olası kusurları arttıkça birçok iyileştirme tekniği üzerinde düşünülmelidir. Çelik çapraz sistemi iyileştirme tekniklerinden biri olup mevcut binaların yatay kuvvetlere karşı güçlendirilmesinde ve rijitliğinin arttırılmasında çok iyi bir yaklaşım sağlar. Ayrıca bu sistemin diğer bir avantajı da iyileştirme sonucunda oluşan kütle artışının çok az olmasıdır. Çünkü bu durum birçok iyileştirme tekniği için önemli bir problemdir.

Bu çalışmada alçak, orta yükseklikte ve yüksek betonarme çerçevelerin çelik çaprazlar kullanılarak güçlendirilmesi yaklaşımı analitik olarak araştırılmıştır. Güçlendirilmiş çerçevelerin yatay yük taşıma kapasiteleri yük kontrollü statik itme analizi yöntemi ile belirlenmiştir. Ön yüklemenin art-germe etkisi de ayrıca incelenmiştir.

Anahtar Kelimeler: Güçlendirme, İyileştirme, Betonarme Çerçeve, Çelik Çaprazlar, Ön Yükleme

To mankind

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INTRODUCTION

1.1 Statement of the Problem

In the past, most of the reinforced concrete structures were designed primarily for gravity loads. They were also designed for lateral forces that may be much smaller than that prescribed by the current codes. An inadequate lap splice in the longitudinal reinforcement and absence of confinement in flexural hinge zones can significantly reduce the strength and ductility of a column. Structures which have such kinds of deficiencies can be prevented from earthquake damages by proper rehabilitation. Therefore, seismic rehabilitation has become an important and popular topic among researchers which is studied and applied to seismically deficient structures.

Recent earthquakes have shown the importance of rehabilitating seismically deficient structures to achieve an acceptable level of performance. This can be achieved by improving the strength, stiffness, and ductility of the existing structures. Significant advancements have been made in the research and development in this field.

There are various rehabilitation techniques and to select the appropriate one, an accurate evaluation of the condition and seismic performance of an existing structure is necessary. An overall evaluation of the seismic performance of an existing structure can be conducted by four different procedures: the linear static procedure, the linear dynamic procedure, the nonlinear static procedure (push-over analysis), and the nonlinear dynamic procedure. After analyzing the structure, the most convenient rehabilitation technique can be chosen.

Rehabilitation techniques can be grouped into two categories: member-level rehabilitation and structural system-level rehabilitation [1]. Member-level rehabilitation is aimed at improving the performance of individual deficient elements such as beams, columns, and the walls. The use of fiber composites and steel jacketing are some examples of this approach. The system-level rehabilitation involves global modifications to the whole structural system [2]. The use of steel bracing system is one of the commonly used system-level rehabilitation techniques.

Steel bracing systems have both practical and economical advantages. The main advantage of this method is that it is not required to rehabilitate the foundation system. since the bracing system does not introduce great additional gravity load to the existing structure and steel bracings are usually installed between existing vertical members. However, increased loading on the existing foundation is possible at the bracing locations and the greater foundation forces are generated in the retrofitted frames under lateral loads so the foundation still must be evaluated. Furthermore, if it is used external steel systems the minimum disruption of the building is obtained.

1.2 Literature Survey

1.2.1 Steel Bracing Systems

The bracing systems can be grouped according to their location in the reinforced concrete frames as internal or external and according to their connection style as eccentric or concentric bracing system.

1.2.1.1 External Bracing System

In external bracing system, the steel trusses are introduced to the exterior frames of the building. Bush, Jones and Jirsa [3] conducted cyclic loading tests on $2/3$-scaled models of a number of structures retrofitted using external bracing. The main frame included deep, stiff spandrel beams and short, flexible columns that were susceptible to shear failure under lateral loads. The bracing system is shown schematically in Figure 1.1. Steel X-bracing system attached to the exterior of the frame using epoxy-grouted dowels was used to strengthen the existing frame. The frame model consisting of two bays and three levels was subjected to statically applied cyclic lateral load. While evaluating the prototype under lateral loading the nominal column shear capacity would be exceeded when only 40% of the column flexural capacity and 30% of the beam flexural capacity were reached.

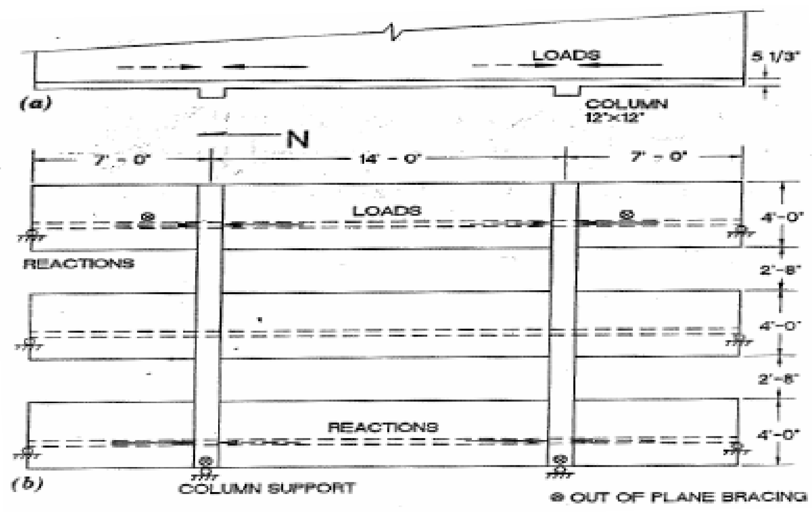


Figure 1.1: Schematic of $2/3$ -scaled frame model: (a) Plan, (b) Elevation. [3]

The model bracing scheme consists of X-braces that were continuous across two stories. The braced model is shown schematically in Figure 1.2.

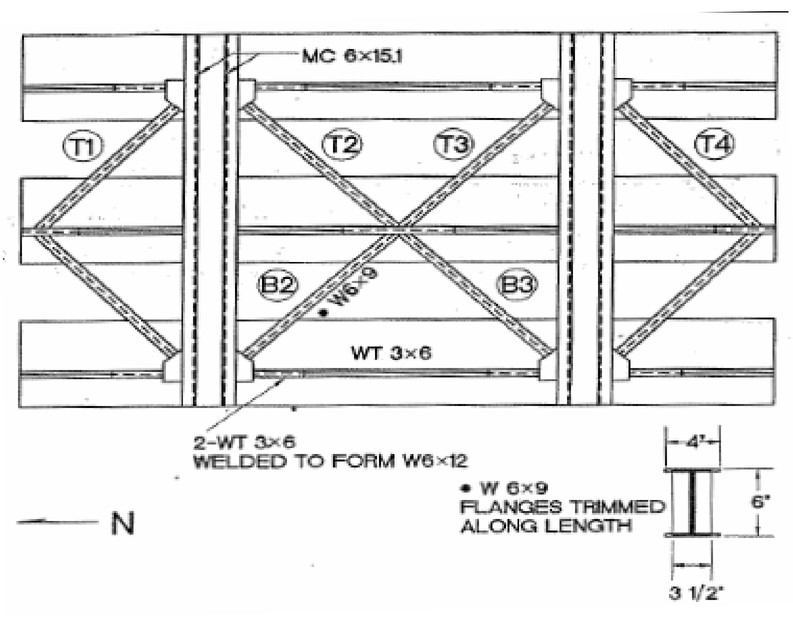
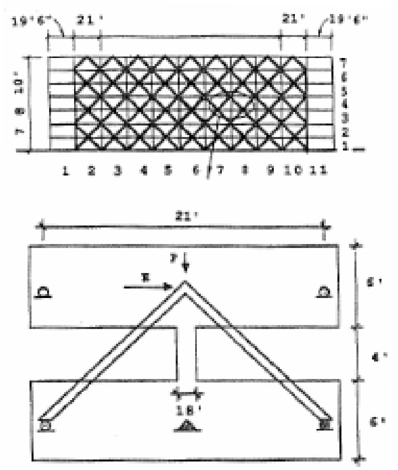


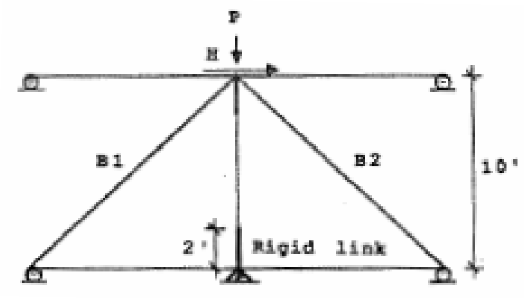
Figure 1.2: Schematic of the model bracing scheme. [3]

The load applied to the main frame was lower than its estimated failure capacity based on shear failure of the two columns so the strengthened frame had an initial stiffness approximately 1.5 times that of the uncracked original frame. Test results showed substantial increases in both lateral stiffness and strength. The maximum load applied to the braced frame was approximately six times the predicted capacity of the original frame. This load was also 2.24 times the predicted design capacity of the strengthened frame. Bracing system elements attached to the side faces of the concrete columns also increased column shear capacities significantly. The lateral capacity of the strengthened frame was governed by brace buckling and eventual connection failures and column shear failures.

Badoux and Jirsa [4] investigated numerically the behavior of RC frames retrofitted with external bracing. Researchers stated that the lateral resistance of the existing frame structures is inadequate for two reasons. First, the perimeter frames, which feature weak short columns, are likely to fail in an undesirable mode. Secondly, code provisions may have been upgraded several times since construction, so that current seismic design loads are more than the original values. An analytical study was carried out to gain understanding into the weak short columns. Subassemblage and analytical model of subassemblage are shown in Figure 1.3.



(a)



(b)

Figure 1.3: (a) Subassemblage, (b) Analytical model of subassemblage. [4]

Inelastic buckling of the braces influences the inelastic cyclic behavior of a braced frame. Instability can be prevented by using braces that yield in compression or buckle elastically at low axial loads. The bracing system improved the strength, stiffness, and ductility of the frame. In their study, after the column failed in shear, the behavior was controlled by the bracing system, and most of the lateral resistance was provided by the brace in tension. And any strength loss in one direction results in a comparable strength loss in the other direction based on tests reported by Umehara and Jirsa [5]. The influence of the brace slenderness ratio of the subassemblage behavior was investigated by changing the kl/r ratio. The elastic capacity of the bracing system was the same for all values of kl/r. Subassemblage responses for kl/r of 40 and 120 were compared. The hysteresis loop for kl/r =40 was better balanced because of the buckling parameter since it controlled buckling and hysteretic behavior of the bracing system. But generally, it is often not possible to keep the brace slenderness low enough. Inelastic buckling can also be prevented by using braces that buckle elastically, such as cables. To avoid buckling of the brace members, and thus improve the ductility of frames, they recommended using cables instead of steel sections for the brace elements.

Based on this study, Badoux and Jirsa recommend that the designer must consider the failure mechanism of the original frame under lateral deformations. The bracing system can improve the frame strength and stiffness, but cannot change the frame mode of failure. The weak column – strong beam frame leads to an unwanted mode of failure so this type frame should be transferred into a strong column – weak beam frame. This can be achieved by strengthening the columns or by weakening the beams. The first option is feasible, but costly. However weakening the beam is attractive because of its simplicity. The aim of the weakening is to decrease the beam flexural capacity enough to guarantee that under lateral loading hinges will develop in the beams before the failure of the column. This can be succeeded by coring or cutting beams. Because of the ductility of the flexural hinges, lateral strength was improved or increased slightly. Inelastic behavior was transferred from the columns to the beams, thus preventing column damage and increasing the energy dissipation capacity of the frame.

1.2.1.2 Internal Bracing System

In internal bracing system, steel trusses or bracing members are introduced to the empty space enclosed by columns and beams of reinforced concrete frames. The effectiveness of using internal steel trusses to retrofit existing reinforced concrete frames was investigated by a number of researchers. They state that such a method allows upgrading the seismic capacity of existing structures.

Maheri and Sahebi [6] recommend the use of internal brace members over internal steel trusses. The investigation included a series of tests conducted on a number of model frames whose detail is shown in Figure 1.4.

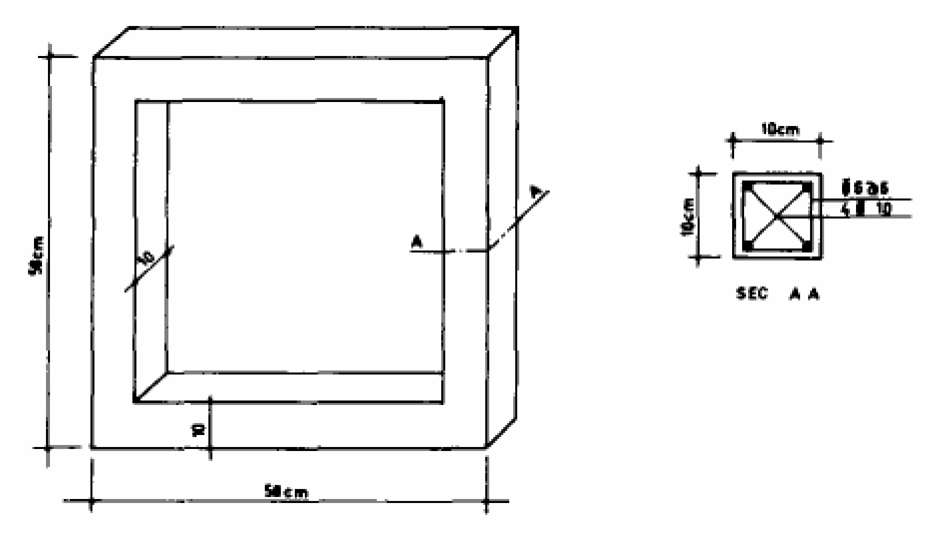


Figure 1.4: Detail of typical test model. [6]

The object of the testing program was to determine the degree of effectiveness of different diagonal bracing arrangements to increase the lateral load capacity of the existing concrete frames and to observe the relative behavior of tension and compression braces. For these investigations, the common diagonal X-bracing system was chosen. Four model frames were selected namely: a concrete frame without bracing, a concrete frame braced with a diagonal tension brace, a concrete frame braced with a diagonal compression brace, and a concrete frame braced with X-bracing. In order to reduce the buckling tendency of the compression brace in the

X-brace system, the two diagonal braces were also connected to each other at their cross-point by a steel plate. The connection to the frame is done by welding the braces to the sides of a steel plate which is welded to an equal angle positioned and pre-cast at the corners of the frame. The connection details are shown in Figure 1.5.

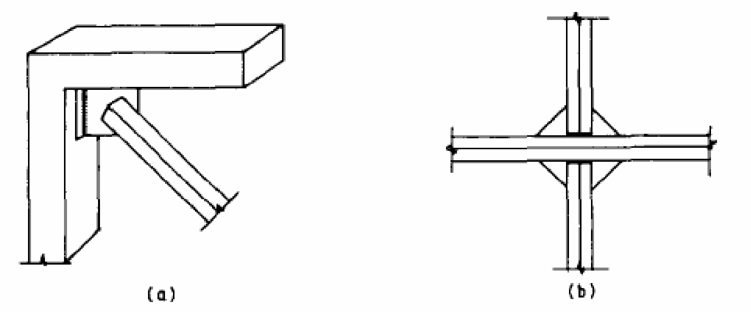
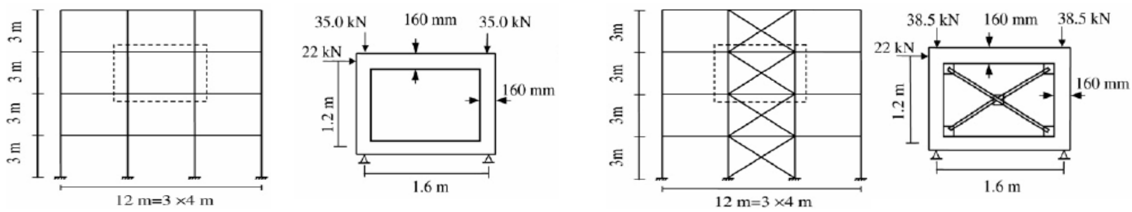


Figure 1.5: Connection detail of; (a) the steel brace to concrete frame, (b) the steel cross braces to each other. [6]

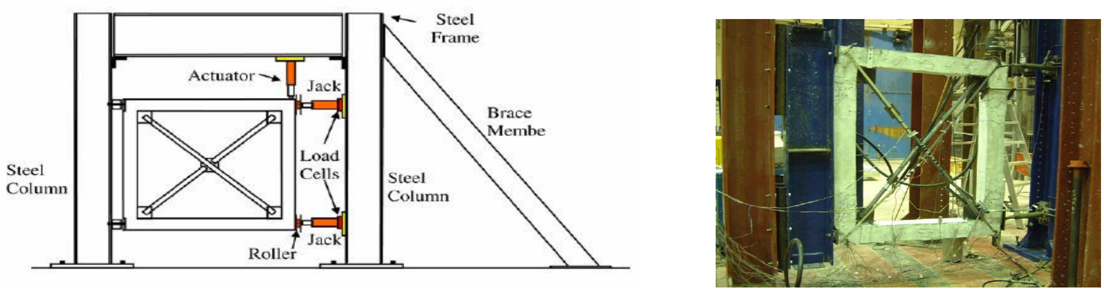
The bending stresses in the concrete frame governed the strength of the system in all four cases and the expected mode of the failure was bending failure. To investigate the shear strength, horizontal cyclic loading was applied to the frame. The experimental test results showed that the ultimate load carried by the frame without bracing is 4.0 tons, the frame with diagonal tension brace is 9.0 tons, the frame with diagonal compression brace is 10.0 tons and the frame with X-bracing is 12.5 tons. An important point of observation was that while testing of cross-braced frame, the rate at which the two braces carried the load was not equal. The more dominant behavior of the tension brace was observed compared to the compression brace initially. The tension brace carried a higher load than the compression brace. However, at higher loads the system showed a non-linear behavior and the dominance of the tension brace started to reduce. The failure of the tension brace occurred at its welded connection to the mid-span plate. After the tension brace was failed, the compression brace buckled under the increased loading. In testing of compression braced frame it was appeared that in the elastic range the load was transferred directly to the concrete frame and the share of load bearing of the compression brace was almost zero. Only at higher loads as the behavior of the frame moved into nonlinear range, the compression brace started to participate in load-bearing. The failure was completed after the compression brace buckled. It was concluded that, a large increase in the shear strength of a concrete frame due to only one diagonal brace acting either in tension or compression was achieved. For the model frames tested the increase in shear strength due to the one brace was 2.5 times that of the frame itself. The strength of the X-braced model frame was measured at four times that of the unbraced frame.

Youssef, Ghaffarzadeh and Nehdi [7] also investigated the use of internal steel bracing for seismic performance of reinforced concrete frames. In their study, the use of concentric internal steel bracing for new construction was investigated experimentally. Two specimens representing a reinforced concrete moment frame with moderate ductility and a braced reinforced concrete frame were designed. A four-storey building and $2/5$-scaled models shown in Figure 1.6 were used in this experimental study with the test set up shown in Figure 1.7.



(a) Moment Frames (b) Braced Frames

Figure 1.6: (a) Ductile RC moment frame and scaled ductile RC moment frame, (b) Braced RC frame and scaled braced RC frame. [7]



(a) **(b)**

Figure 1.7: (a) Schematic of the test setup, (b) Photo of the test setup. [7]

Test results showed that the braced frame resisted higher lateral loads than the moment frame and provided adequate ductility. The ultimate load capacity and the initial stiffness of the braced reinforced concrete frame was nearly 2.5 times that of the reinforced concrete moment frame. Before buckling of the compression brace, the lateral stiffness of the braced frame was more than that of the moment frame. After buckling of the compression brace, the lateral stiffness of the braced frame dropped. Observations revealed that at low drift levels, the energy dissipated by the braced frame was less than that by the moment frame. The reason for this was mainly due to the initial high stiffness of the braced frame. At higher levels of drift, the energy dissipated by the braced frame was much higher than that by the moment frame. This demonstrated that the seismic performance of the braced frame is expected to be superior to that of the moment frame. Since the frame of the braced frame system was newly constructed, this study also indicated that the use of the steel bracing instead of shear walls for new construction has many advantages: reducing the weight of the structure and thus reducing the seismic loads, and increasing the ductility of the structure.

Gündoğmuş [8] investigated the repair and strengthening of damaged reinforced concrete frames with steel infill frame and prestressing bars. The aim of this study was to investigate the effectiveness and behavior of a new strengthening system. The system mainly composed of a steel infill frame and prestressed bars used as diagonals. For this reason, two experiments were performed. In the first test, a two story one bay frame, which was strengthened with the proposed system, and a two story one bay frame strengthened with steel infill brick wall, were tested simultaneously. In the second test, prestressing strands were used as diagonals instead of prestressing bars and infill brick was replaced with steel angle sections. These two frames were tested simultaneously under the effect of cyclic loading.

Test results showed that the use of new system for strengthening of existing reinforced concrete frames against seismic action seems to be feasible. The system increased both strength and stiffness significantly under lateral loads. Increase in strength is approximately six times of the bare frame’s strength. It was also seen from the results that the framing effect of bar supporting structure significantly affect the diagonal bars. Very rigid corners prevent the working of bars and bars do not take any load. Thus only the frame is effective to carrying the lateral loads.

1.2.1.3 Eccentric and Concentric Bracing Systems

As it is mentioned the bracing system can also be classified as eccentric and concentric bracing systems. Each of these systems has some advantages as well as disadvantages. The most important advantage of the eccentrically braced framing systems is its good ductility at overloads. The actions are transferred to the braces by bending and shear in an active link. This link prevents buckling of the braces. The active link is one of the most important members of this bracing system, and this member has to be designed to remain elastic at low load levels, and to deform inelastically during overloading of the structure. So, the system dissipates large amounts of energy. Concentric braces also improve strength and stiffness, but the energy dissipation capacity and inelastic behavior remain poor due to the buckling of the diagonal brace.

Ghobarah and Abou Elfath [9] have investigated analytically the seismic performance of a low-rise non-ductile reinforced concrete building rehabilitated using eccentric steel bracing. The purpose of the study was to investigate the effect of the rehabilitation in the stiffness and the energy dissipation capacity. In the system rehabilitated by using eccentric bracing, the forces are transferred to the brace members through bending and shear forces developed in the ductile steel link. Different brace patterns were used. These patterns can be V-bracing (a), K-bracing (b), X-bracing (c), and Y-bracing (d), as shown in Figure 1.8.

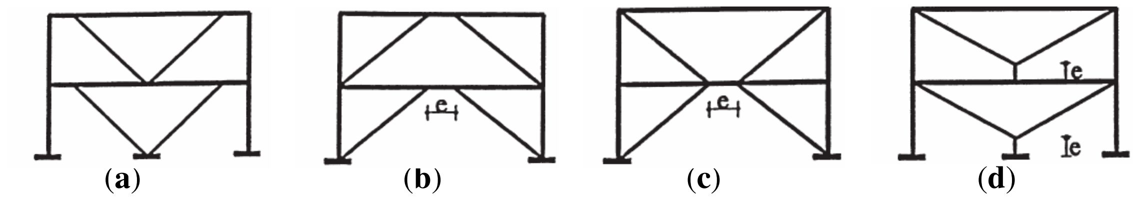


Figure 1.8: Various types of eccentrically steel bracing frames. (a) V-bracing, (b) K-bracing, (c) X-bracing, (d) Y-bracing. [9]

The seismic performance of the rehabilitated reinforced concrete frames was investigated using nonlinear static push-over analysis and dynamic time–history analysis and the link was modeled using tri-linear moment and shear force representations. In this study, the most important points were that steel brace members should be designed to behave elastically when subjected to an earthquake loading and the connection between the vertical shear link and the reinforced concrete frame should have sufficient capacity to transmit forces when subjected to seismic loads.

In the study, a three-story building was rehabilitated by using three rehabilitation alternatives so that the effect of the distribution of the steel braces can also be investigated. One of the three cases was concentric and the other two were eccentric steel bracing systems as shown in Figure 1.9.

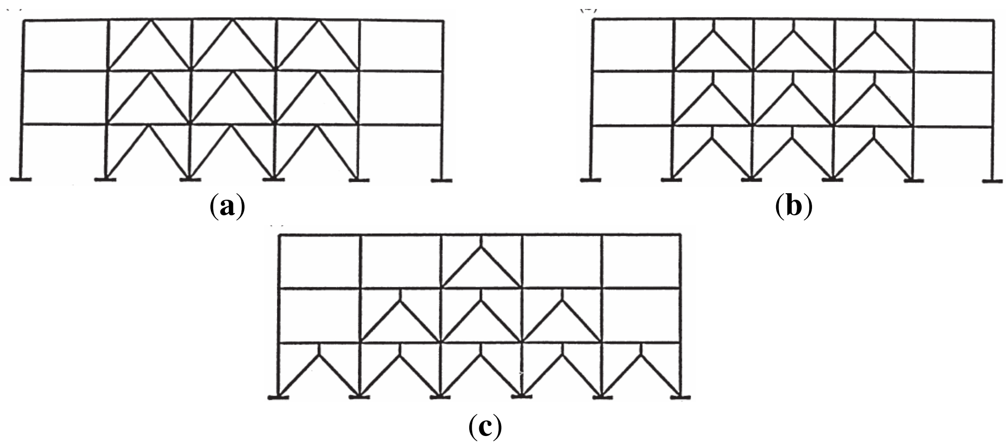


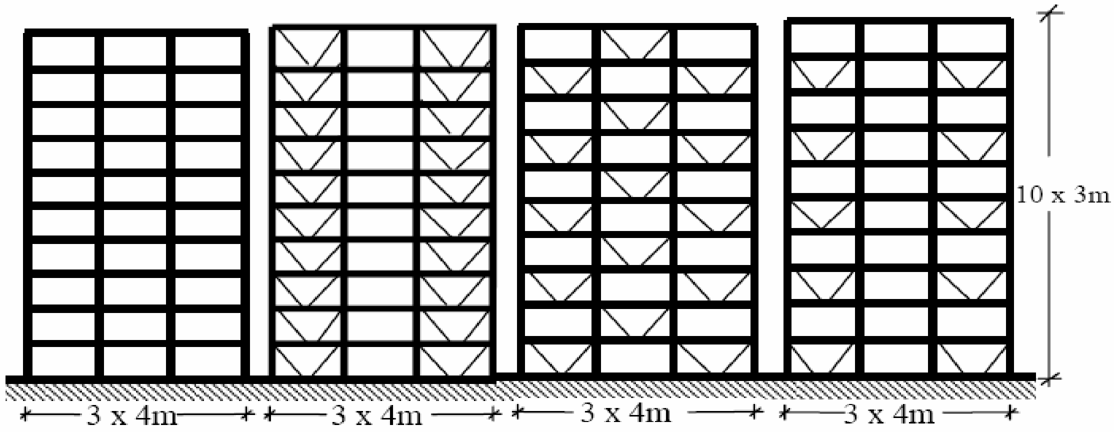
Figure 1.9: Rehabilitation cases: (a) Concentric bracing, (b) Eccentric bracing, (c) Eccentric bracing. [9]

The lateral load capacity was 1.7 times, 1.6 times and 1.9 times that of the existing building for the rehabilitated cases (a), (b) and (c), respectively. Although, the same number of bracing elements was used in the two eccentric bracing rehabilitation cases, the pyramidal shaped eccentric rehabilitation case had higher lateral load capacity than the other. The mean level of deformations and damages were lower in the eccentric bracing cases than the concentric bracing case. The highest stiffness was obtained in the case (c). This shows that the distribution of the steel bracing components over the height of the building affects the behavior of the rehabilitated structure. This, in turn, leads to a change in the characteristics of the plastification mechanism. Therefore, in order to obtain a uniform distribution of story drift, the researchers have suggested that the brace strength over the height of the building be distributed.

1.2.2 Brace Layout Effect

Laying out the bracings has an important effect on the retrofitting of reinforced concrete frames. Creation of some undesirable weak links must be avoided in the process. From structural point of view, it may be desirable to brace as many bays of the frame as possible, so that increases in strength and the stiffness are distributed uniformly. However, cost and functional considerations may limit the number of the braced bays. An exterior bracing system is also advantages because of the torsional behavior of the structure under earthquake effects. Increasing the exterior bracing maximize the structural symmetry and the torsional resistance. However, if only the exterior frames are strengthened, the slabs have to be strong enough to carry the additional seismic shear to exterior frames.

The effect of the distribution of the steel bracings over the story height on the rehabilitation of the reinforced concrete frame building was investigated by Korkmaz [10]. He studied the seismic behavior of reinforced concrete frame structures strengthened with eccentric steel bracing analytically. In the analyses, 10-story reinforced concrete frame structures were studied by using the program DRAIN 2DX [11] and the dimensions of the structural members were determined based on the requirements of the Turkish codes TS500 [12] and ABYYHY [13]. Existing structure and three rehabilitated cases shown in Figure 1.10 were investigated. The aim of the study was to determine the most suitable rehabilitation scheme.



Existing Structure Case I Case II Case III

Figure 1.10: Existing structure and three rehabilitated cases. [10]

After the push-over analysis, it was seen that the lateral load capacity of the rehabilitated structure was two times that of the existing structure. According to capacity curves of these four cases, the Case II had the maximum lateral load capacity and the Case I displayed the best results for the lateral displacement demand. However, if the economical aspects are also taken into consideration, the Case II was the most convenient one among all cases. So, this study has shown the importance of the distribution of the steel bracings over the height of the reinforced concrete frame structures.

CHAPTER 2

ANALYSIS PROCEDURE

2.1 Introduction

In this study, an alternative approach to strengthening reinforced concrete frames using steel bracing was investigated analytically. The main advantages of the proposed procedure compared to commonly employed practice are; benefiting from the preloading of steel members and not requiring connection between steel bracing and the reinforced concrete frame at the beam-column joints of the existing frame. The preloaded steel members located adjacent to the existing reinforced concrete frame columns were used to reduce the axial compression load on the existing reinforced concrete columns. Generally, most of the existing buildings have deficiencies at the beam-column joints due to lack of transverse reinforcement and lapped splice with inadequate splice length at the joint level. These deficiencies lead to weakness of the beam-column joints. Since there is not any connection between steel members and reinforced concrete frame at these points, this rehabilitation technique does not disturb the existing reinforced concrete frame at these critical sections.

2.2 Computer Modeling

Frames were modeled using SAP 2000 Integrated Software for Structural Analysis and Design [14]. Each model is composed of three main groups of structural components. These are the reinforced concrete bare frame, the steel frames inserted into frame bays and the steel X-bracing system in each bay which is attached to internal steel frame.

A load controlled pushover analysis was conducted using an inverted triangular lateral load distribution representing seismic effect on the structure. Each model of the final structure was analyzed using the stage analysis property of SAP 2000.

The main steps of the stage analysis are as follows;

- Modeling of the reinforced concrete bare frame,
- Adding steel column members,
- Introducing preloading to these steel column members at selected ratios of the existing axial load in the adjacent reinforced concrete columns,
- Adding steel beam members,
- Adding steel bracing members,
- Performing pushover analysis on the model by introducing lateral loads with small increments.

Since the steel bracing rehabilitation technique can be used in any building with a reinforced concrete frame structural system having different number of stories, span lengths, concrete compressive strength, column dimensions, …etc., several parameters were investigated in this study. While choosing these parameters, the building stock in Turkey was taken into consideration. The parameters which are deemed critical and selected for investigation are summarized in Table 2.1.

Table 2.1: Selected parameters for the rehabilitation of R/C frames by steel X- bracing.

Parameter	Range of Parameter					
Building Height (# of Stories)	3		5		8	
Building Grid Dimensions (m)	4	6	4	6	4	6
R/C Column Section Size (cm)	30x30	40x40	40x40	50x50	50x50	65x65
Concrete Strength (MPa)	C16, C20 C25, C30	C16, C20 C25, C30	C16, C20 C25, C30	C16, C20 C25, C30	C16, C20 C25, C30	C16, C20 C25, C30
Bracing System Preload Ratio (% of R/C Column Axial Load)	0, 10 20, 30	0, 10 20, 30	0, 10 20, 30	0, 10 20, 30	0, 10 20, 30	0, 10 20, 30

In this study, the building height (number of stories), the plan dimensions of the reinforced concrete framing system (bay width), the strength class of concrete material, the reinforced concrete structural system column dimensions, and the amount of preloading to be applied to the columns of the steel bracing system are selected as controlling parameters and investigated. Based on the majority of the building stock in Turkey 3, 5 and 8-story high reinforced concrete frames are selected as representative of low, medium and relatively high rise building frames, respectively. The range of concrete strength classes selected for investigation are C16, C20, C25 and C30 with characteristic compressive strengths of 16 MPa, 20 MPa, 25 MPa, and 30 MPa, respectively. Typical reinforcement steel yield strength is taken as 420 MPa. For simplicity, the design live load and dead load are taken totally as 1.0 ton/m^2 and a typical storey height is assumed to be 3.0 m The column dimensions are selected separately for each bay width and the number of stories in the building in such a way that the maximum axial compressive load in the column under service conditions is near the ultimate level allowed by major design codes. Finally, the amount of longitudinal reinforcement for each column is assumed to be approximately 1% of the column sectional area which is the minimum amount required by most design codes.

Essentially the following seven structures are studied;

S3-B4: Single-bay 3-story frame with 4 m bay width.
S3-B6: Single-bay 3-story frame with 6 m bay width.
S5-B4: Single-bay 5-story frame with 4 m bay width.
S5-B6: Single-bay 5-story frame with 6 m bay width.
S8-B4: Single-bay 8-story frame with 4 m bay width.
S8-B6: Single-bay 8-story frame with 6 m bay width.
S3-2B4: Two-bay 3-story frame with 4 m bay width.

Each of the seven main structures is studied for the concrete strength classes of C16, C20, C25, and C30, and for each case the following nine alternative rehabilitation schemes are investigated;

BF: R/C frame only (Bare frame).
P0: R/C frame strengthened by steel X-bracing in each bay. Bracing ends connected by steel edge members all around, no anchorage, no preloading.
P10: R/C frame strengthened by steel X-bracing in each bay. Bracing ends connected by steel edge members all around, no anchorage, 10% preload.
P20: R/C frame strengthened by steel X-bracing in each bay. Bracing ends connected by steel edge members all around, no anchorage, 20% preload.
P30: R/C frame strengthened by steel X-bracing in each bay. Bracing ends connected by steel edge members all around, no anchorage, 30% preload.
NB: R/C frame strengthened by steel X-bracing in each bay. Bracing ends connected by vertical steel edge members only, no anchorage, no preloading.

WA: R/C frame strengthened by steel X-bracing in each bay. Bracing ends anchored to R/C frame, no preloading.

UA: R/C frame strengthened by steel X-bracing in each bay. Bracing ends not anchored to R/C frame, no preloading.

SUA: R/C frame strengthened by stronger steel X-bracing in each bay. Bracing ends not anchored to R/C frame, no preloading.

The horizontal, vertical, and diagonal components of the steel bracing system are selected separately for each case. The sections are kept unchanged while investigating the alternative rehabilitation schemes of a given structure. The only exception to this rule is the rehabilitation schemes of **SUA** in which stronger brace sections are selected. For the rehabilitation schemes of **UA** and **NB**, the final stress ratio in the braces at the lateral load level of ultimate capacity is the same as that for the rehabilitation scheme of **WA** and **P0,** respectively. The steel section dimensions are selected as the minimum required to utilize the inherent capacity of the initial R/C frame to its fullest extend. Therefore, in all cases except **UA**, the ultimate capacity of the resulting rehabilitated structure is always controlled by the failure of the original R/C frame.

The modulus of elasticity for steel material of the bracing system and the concrete material of the R/C frame are taken as 200 GPa and 24.8 GPa, respectively. The yield stress for steel is taken as f_y = 235 MPa, and the ultimate strength as f_u = 360 MPa. The ultimate capacity of the bracing system under lateral loads is determined based on the requirements of the design code AISC [15] while that of the R/C frame is determined based on the requirements of the design code ACI [16].

2.3 Description of the Mathematical Models

Mathematical model of the test frames is composed of 1-D frame elements representing the beams, columns and the steel bracing system, and rigid links at beam-column junctions representing the rigid zones at joints. These rigid links also serve as anchor bolts of the bracing system. The no anchorage situation is modeled by utilizing the no-tension property of SAP 2000 so that the links do not take any tension. General representation of the mathematical model of the rehabilitation schemes is shown in Figure 2.1 and the selected sectional properties for different rehabilitation schemes are shown in Table 2.2.

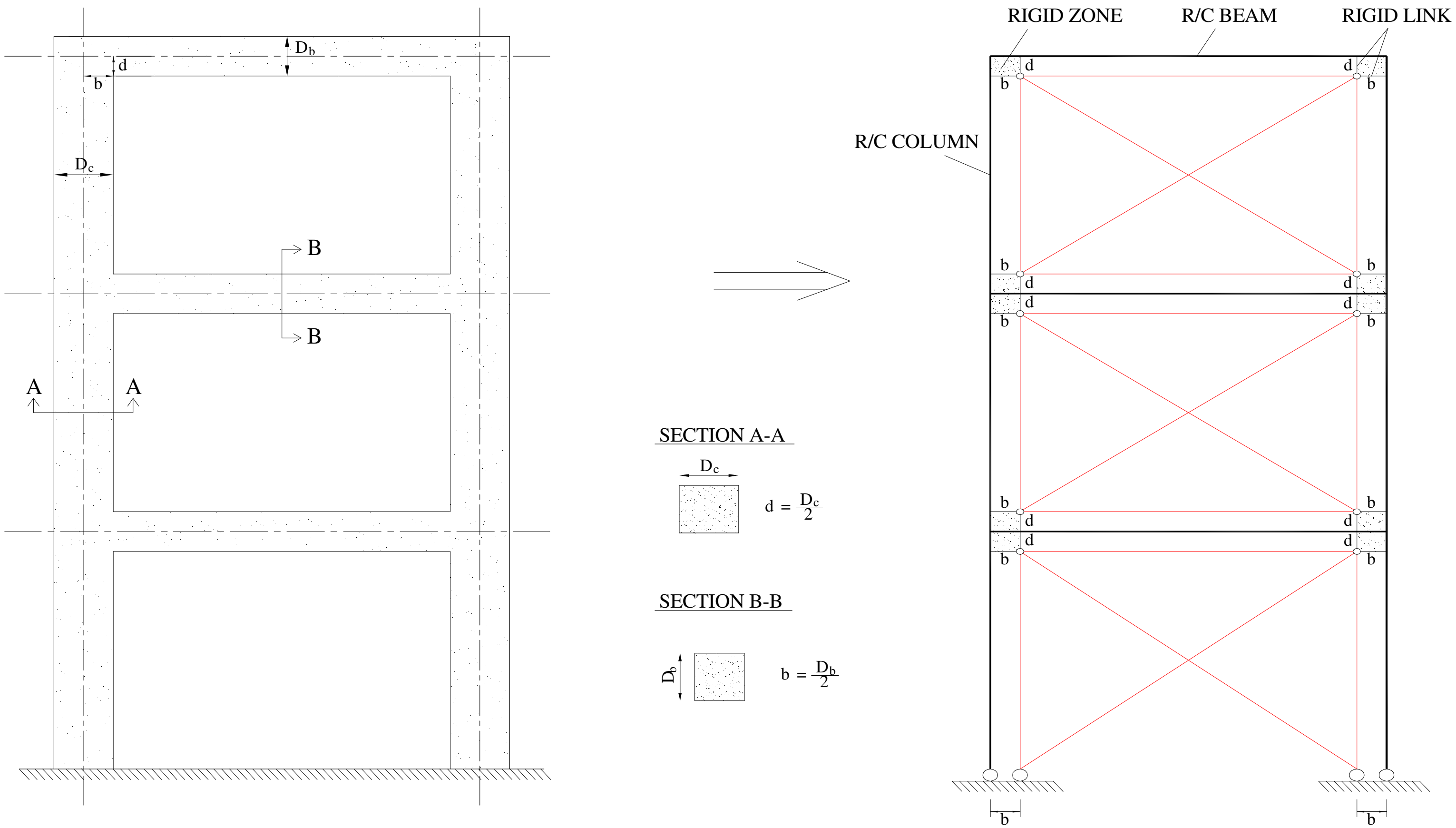


Figure 2.1: Schematic of frame Mathematical Model.

Table 2.2: Selected sectional properties for the rehabilitation of R/C frames by steel X-bracing.

R/C Frame	Rehabilitation Scheme	R/C Frame Sections		Steel Bracing System Sections		
		Beam (cm)	Column (cm)	Beam	Column	Braces
S3-B4	BF	30x40	30x30	-	-	-
	P0, P10, P20, P30			UPN 200	UPN 200	TUBO 220x110x7.1
	NB			UPN 200	-	TUBO 220x110x7.1
	WA, UA			-	-	TUBO 220x110x7.1
	SUA			-	-	TUBO 220x110x8
S3-B6	BF	30x40	40x40	-	-	-
	P0, P10, P20, P30			UPN 200	UPN 300	TUBO 380x190x10
	NB			UPN 200	-	TUBO 380x190x10
	WA, UA			-	-	TUBO 380x190x10
	SUA			-	-	TUBO 380x10x12.5
S5-B4	BF	30x40	40x40	-	-	-
	P0, P10, P20, P30			UPN 200	TUBO 160x160x10	TUBO 220x110x7.1
	NB			UPN 200	-	TUBO 220x110x7.1
	WA, UA			-	-	TUBO 220x110x7.1
	SUA			-	-	TUBO 220x110x8
S5-B6	BF	30x40	50x50	-	-	-
	P0, P10, P20, P30			UPN 200	TUBO 200x200x16	TUBO 380x190x12.5
	NB			UPN 200	-	TUBO 380x190x12.5
	WA, UA			-	-	TUBO 380x190x12.5
	SUA			-	-	TUBO 380x190x12.5
S8-B4	BF	30x40	50x50	-	-	-
	P0, P10, P20, P30			UPN 200	TUBO 200x200x16	TUBO 220x110x7.1
	NB			UPN 200	-	TUBO 220x110x7.1
	WA, UA			-	-	TUBO 220x110x7.1
	SUA			-	-	TUBO 280x140x7.1
S8-B6	BF	30x40	65x65	-	-	-
	P0, P10, P20, P30			UPN 240	TUBO 200x200x35	TUBO 380x190x12.5
	NB			UPN 240	-	TUBO 380x190x12.5
	WA, UA			-	-	TUBO 380x190x12.5
	SUA			-	-	TUBO 400x200x12.5
S3-2B4	BF	30x40	30x30	-	-	-
	P0, P10, P20, P30			UPN 200	UPN 200	TUBO 200x100x5.9
	NB			UPN 200	-	TUBO 200x100x5.9
	WA, UA			-	-	TUBO 200x100x5.9
	SUA			-	-	TUBO 220x110x5.9

CHAPTER 3

ANALYSIS RESULTS

3.1 Bare Frames Capacities

In order to establish the reference values, the lateral load capacity of each R/C bare frame was determined first. The ultimate lateral load capacities of Bare Frame (**BF**) models are shown in Figures 3.1 – 3.4. It is seen from the figures that the lateral load capacity increases with the increasing concrete strength, as expected. It also seen that the relative increase is more pronounced for wider bay widths.

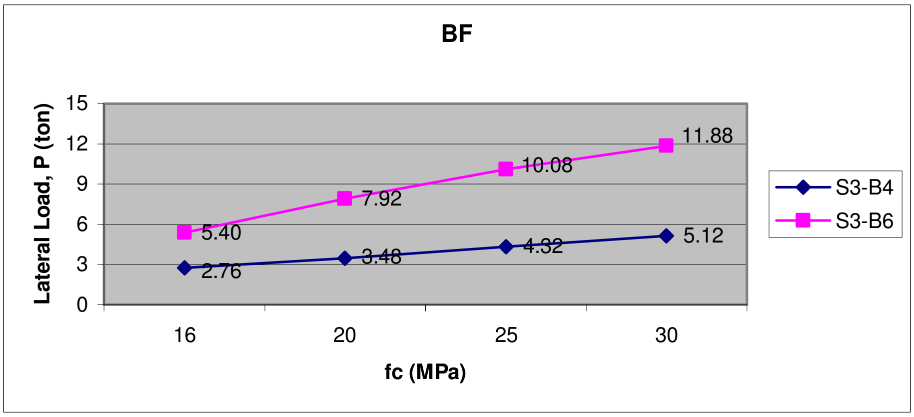


Figure 3.1: Influence of concrete strength on the ultimate lateral load capacity of Bare Frames of S3-B4 and S3-B6.

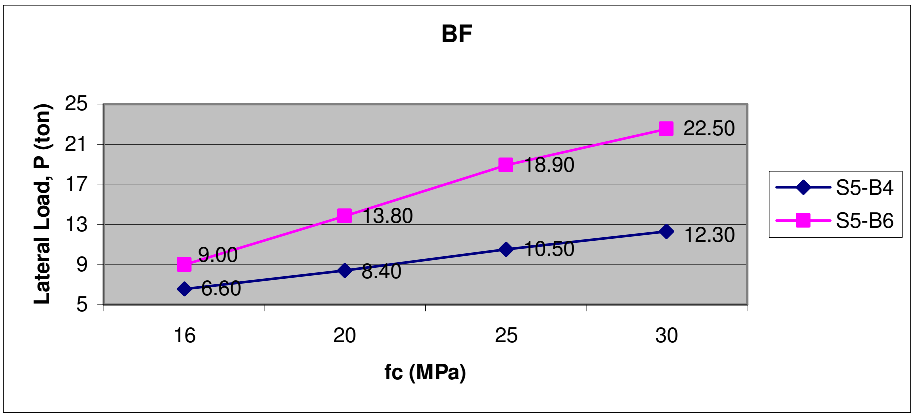


Figure 3.2: Influence of concrete strength on the ultimate lateral load capacity of Bare Frames of S5-B4 and S5-B6.

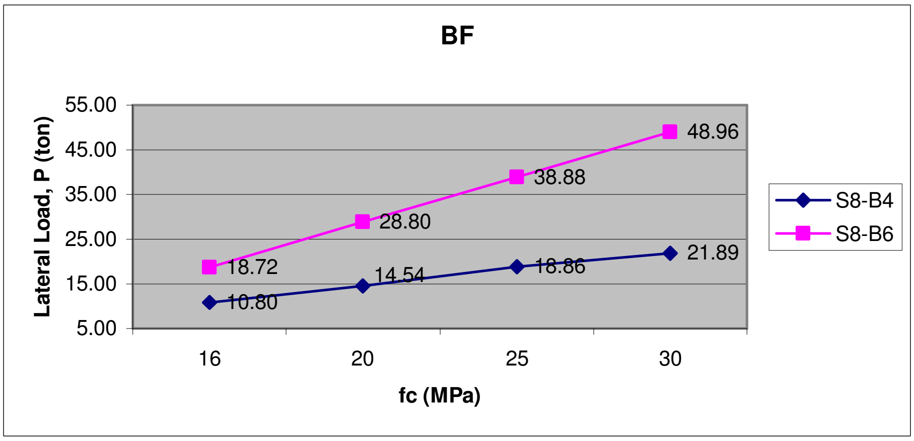


Figure 3.3: Influence of concrete strength on the ultimate lateral load capacity of Bare Frames of S8-B4 and S8-B6.

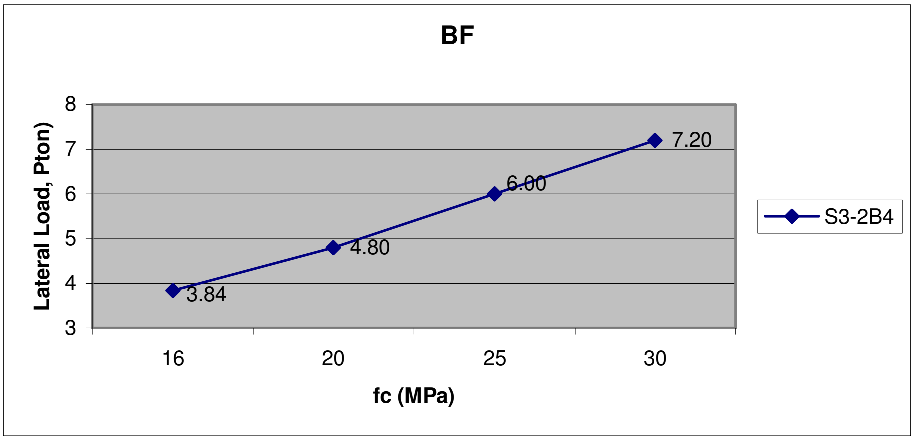


Figure 3.4: Influence of concrete strength on the ultimate lateral load capacity of Bare Frame of S3-2B4.

3.2 Frames Strengthened by Steel X-Bracing Enclosed with Steel Edge Members

Reinforced concrete frames strengthened by steel X-bracing enclosed with steel edge members have been studied for the influence of preloading in the bracing system. The preloading is applied to the columns of the bracing system perimeter frame connecting the diagonal brace ends.

3.2.1 Single-Bay Three-Storey Frames

Reinforced concrete frames strengthened with steel X-bracing surrounded by a closed frame of steel edge members have been studied for the cases of no preloading (**P0**), 10% preloading (**P10**), 20% preloading (**P20**), and 30% preloading (**P30**). The preloading is in the columns of the enclosing frame of the steel bracing system. The variation in the ultimate lateral load capacity of the rehabilitated frame structures as a function of the concrete strength levels of C16, C20, C25 and C30 are given below.

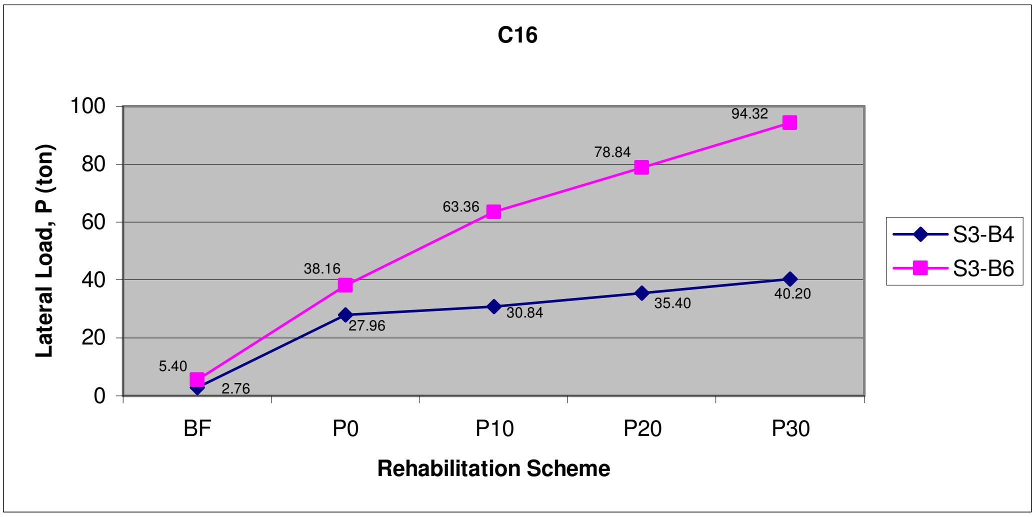


Figure 3.5: Effect of preloading on S3-B4 and S3-B6 frames for C16 concrete.

Figure 3.5 shows the effect of preloading for concrete compressive strength of $f_c^{'}=16$ MPa in S3-B4 and S3-B6 frame structures. It is seen that for S3-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 2.76 tons and it is increased up to 27.96 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 10.1 times that of the Bare Frame ultimate capacity. It is also evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. The columns of the R/C frame fail under the combined effect of compression and bending. The preloading applied to steel bracing system reduces the existing compression in the R/C columns which results in a direct increase in the lateral load capacity of the structural system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 30.84, 35.40, and 40.2

tons, respectively. The maximum lateral load capacity reached at 30% preloading level is approximately 14.6 times that of the Bare Frame.

For S3-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 5.40 tons and it is increased up to 38.16 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 7.1 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 63.36, 78.84, and 94.32 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 17.5 times that of the initial Bare Frame.

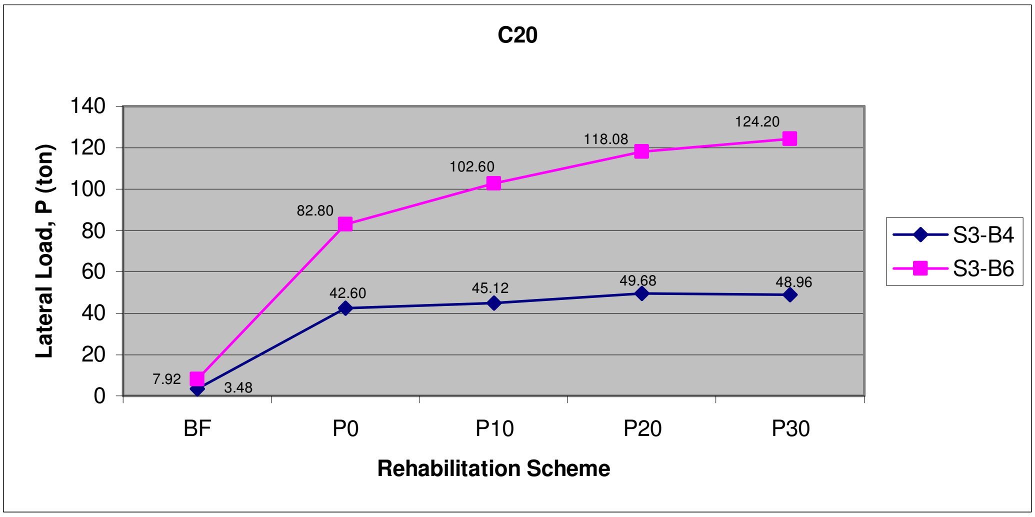


Figure 3.6: Effect of preloading on S3-B4 and S3-B6 frames for C20 concrete.

Figure 3.6 shows the effect of preloading for concrete compressive strength of $f_c' = 20$ MPa in S3-B4 and S3-B6 frame structures. It is seen that for S3-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 3.48 tons and it is increased up to 42.60 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 12.2 times that of the Bare Frame ultimate capacity. It is seen that, in general, the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. However, there is a small slump in the ultimate lateral load capacity of S3-B4 structure beyond a preloading level of 20% (**P20**). This reduction in the capacity is due to the changing failure mode of the structure. Although, for lower levels of preloading the failure of the R/C structure is controlled by the excessive compression in the R/C columns it becomes the excessive tension for higher levels of preloading. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 45.12, 49.68, and 48.96 tons, respectively. The maximum lateral load capacity reached at 20% preloading level is approximately 14.3 times that of the Bare Frame.

For S3-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 7.92 tons and it is increased up to 82.80 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 10.5 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 102.60, 118.08, and 124.20 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 15.7 times that of the initial Bare Frame.

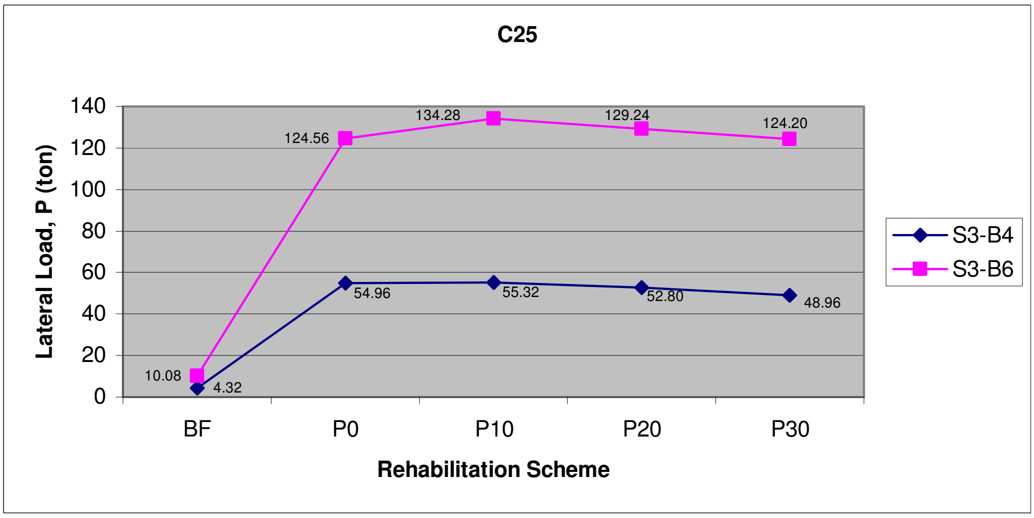


Figure 3.7: Effect of preloading on S3-B4 and S3-B6 frames for C25 concrete.

Figure 3.7 shows the effect of preloading for concrete compressive strength of $f_c^{'} = 25$ MPa in S3-B4 and S3-B6 frame structures. It is seen that for S3-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 4.32 tons and it is increased up to 54.96 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 12.7 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 55.32, 52.80, and 48.96 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 12.8 times that of the Bare Frame.

For S3-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 10.08 tons and it is increased up to 124.56 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 12.4 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 134.28, 129.24, and 124.20 tons, respectively. The maximum lateral load capacity is reached at a preload level of 10% is approximately 13.3 times that of the Bare Frame. As in the case of S3-B4 frame, a gradually decreasing trend with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system is observed also in the lateral load capacity of the rehabilitated structures of S3-B6 frame for the same reason.

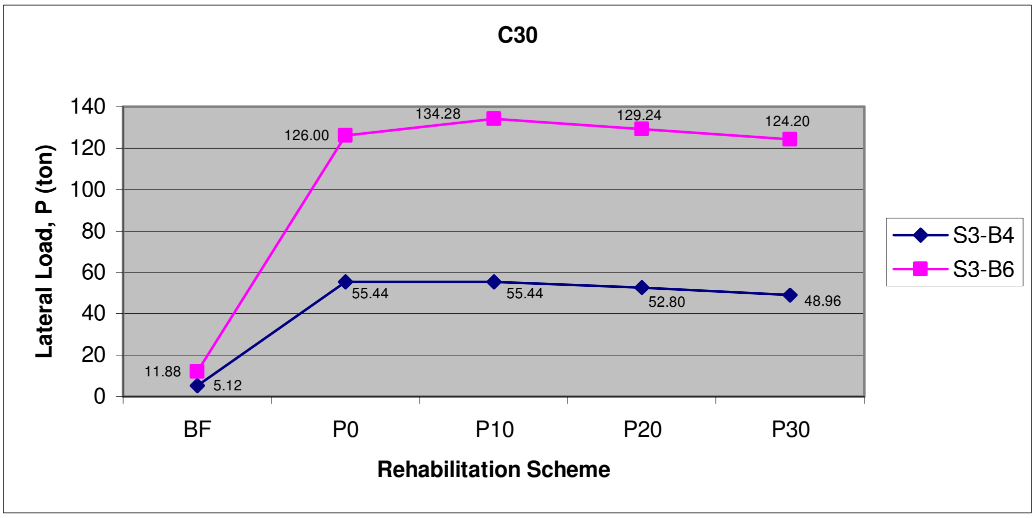


Figure 3.8: Effect of preloading on S3-B4 and S3-B6 frames for C30 concrete.

Figure 3.8 shows the effect of preloading for concrete compressive strength of $f_c^{'} = 30$ MPa in S3-B4 and S3-B6 frame structures. It is seen that for S3-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 5.12 tons and it is increased up to 55.44 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 10.8 times that of the Bare Frame ultimate capacity. A gradually decreasing trend similar to C25 concrete is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20** and **P30**) the ultimate lateral load capacity is increased to 55.44, 52.80, and 48.96 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 10.8 times that of the Bare Frame.

For S3-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 11.88 tons and it is increased up to 126.00 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 10.6 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 134.28, 129.24, and 124.20 tons, respectively. The maximum lateral load capacity is reached at a preloading level of 10% is approximately 11.3 times that of the Bare Frame. Similar to the case of S3-B4 frame, a gradually decreasing trend with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system is observed also in the lateral load capacity of the rehabilitated structures of S3-B6 frame for the same reason.

The influence of preloading on the effectiveness of the rehabilitation schemes using closed-frame steel X-bracing for three-storey R/C frames is shown in Figures 3.9 and 3.10. It is seen that the improvement continues with the increasing level of preloading unless the mode of failure switches from compression to tension in the columns. The relative increase in the ultimate compressive load capacity with the increasing concrete strength is approximately 10 times that of the tensile load capacity while the increase in the column axial forces due to lateral loading is nearly identical.

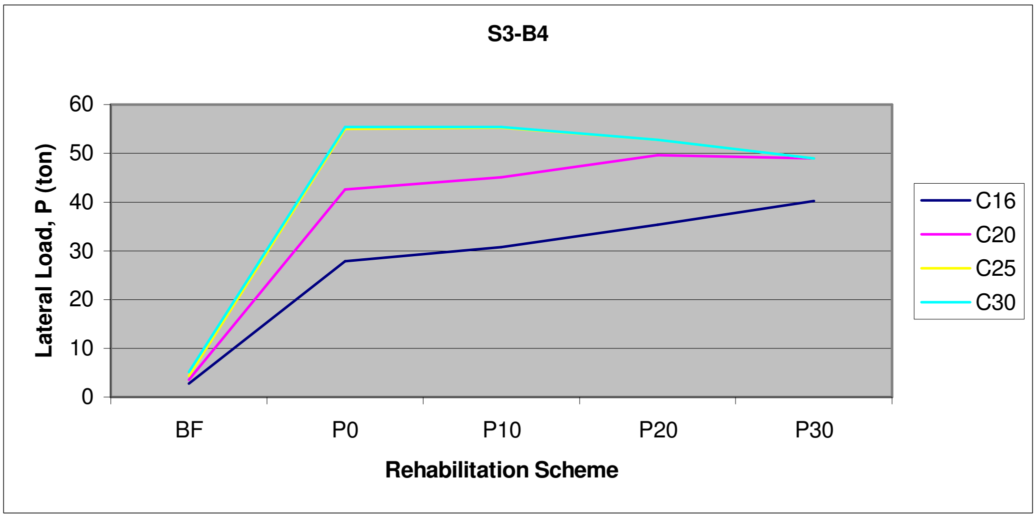


Figure 3.9: Influence of preloading on the lateral load capacity of S3-B4 frames.

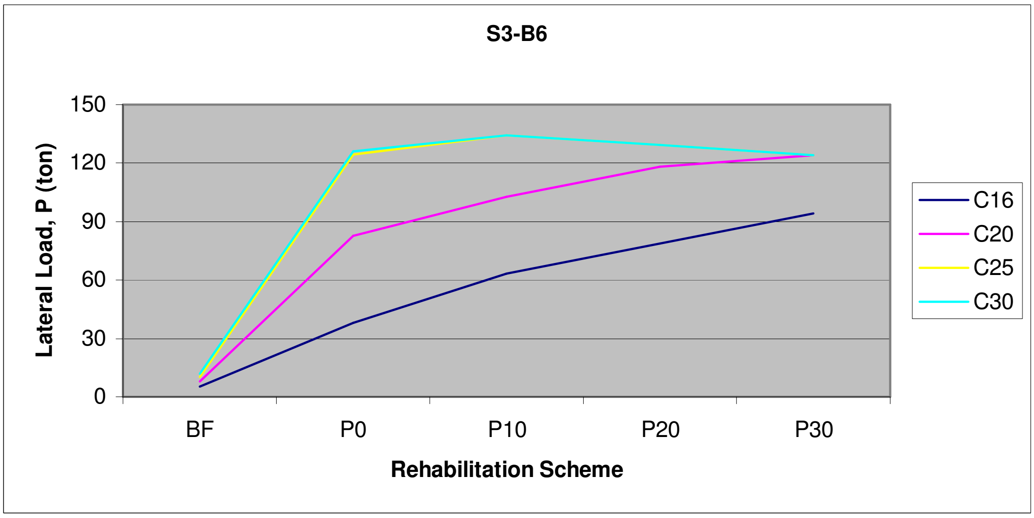


Figure 3.10: Influence of preloading on the lateral load capacity of S3-B6 frames.

3.2.2 Single-Bay Five-Storey Frames

The parametric study procedure followed for single-bay three-storey reinforced concrete frame structures strengthened with closed-frame steel X-bracing scheme has been repeated for single-bay five-storey reinforced concrete frame structures for the same concrete strength classes and the same preloading levels. The results are summarized and discussed below.

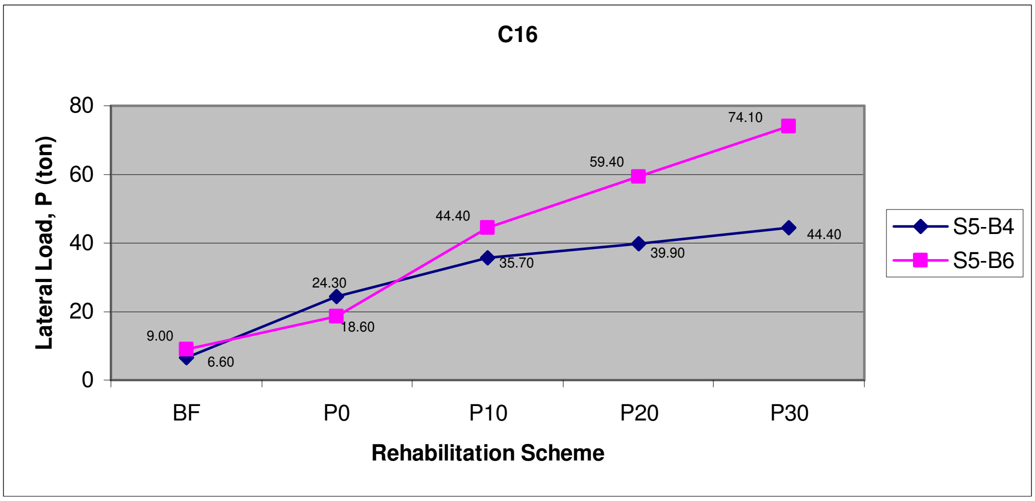


Figure 3.11: Effect of preloading on S5-B4 and S5-B6 frames for C16 concrete.

Figure 3.11 shows the effect of preloading for concrete compressive strength of f_c'=16 MPa in S5-B4 and S5-B6 frame structures. It is seen that for S5-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 6.60 tons and it is increased up to 24.30 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 3.7 times that of the Bare Frame ultimate capacity. It is also evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 35.70, 39.90, and 44.40 tons, respectively. The maximum lateral load capacity reached at 30% preloading level is approximately 6.7 times that of the Bare Frame.

For S5-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 9.00 tons and it is increased up to 18.60 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 2.1 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 44.40, 59.40, and 74.10 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 8.2 times that of the initial Bare Frame.

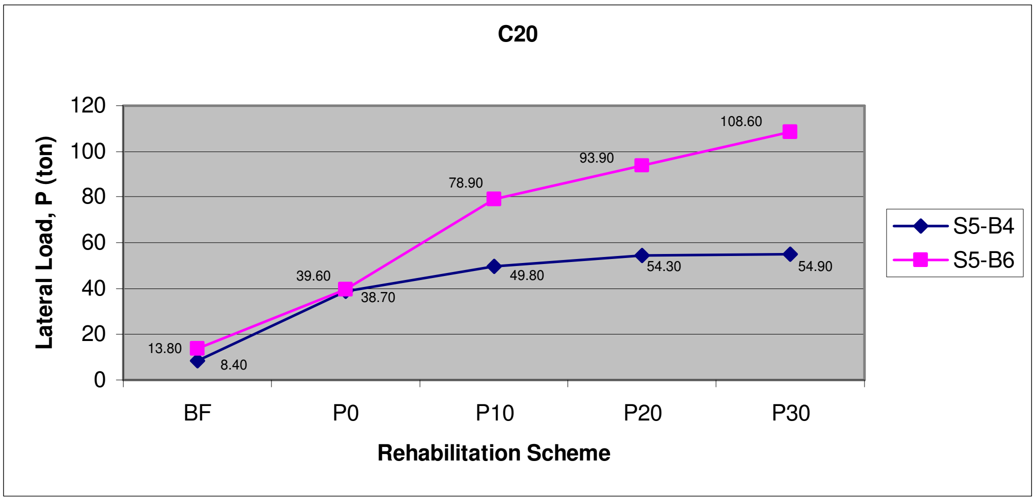


Figure 3.12: Effect of preloading on S5-B4 and S5-B6 frames for C20 concrete.

Figure 3.12 shows the effect of preloading for concrete compressive strength of $f_c^{'}=$ 20 MPa in S5-B4 and S5-B6 frame structures. It is seen that for S5-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 8.40 tons and it is increased up to 38.70 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 4.6 times that of the Bare Frame ultimate capacity. It is also evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 49.80, 54.30, and 54.90 tons, respectively. The maximum lateral load capacity reached at 30% preloading level is approximately 6.5 times that of the Bare Frame.

For S5-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 13.80 tons and it is increased up to 39.60 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 2.9 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 78.90, 93.90, and 108.60 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 7.9 times that of the initial Bare Frame.

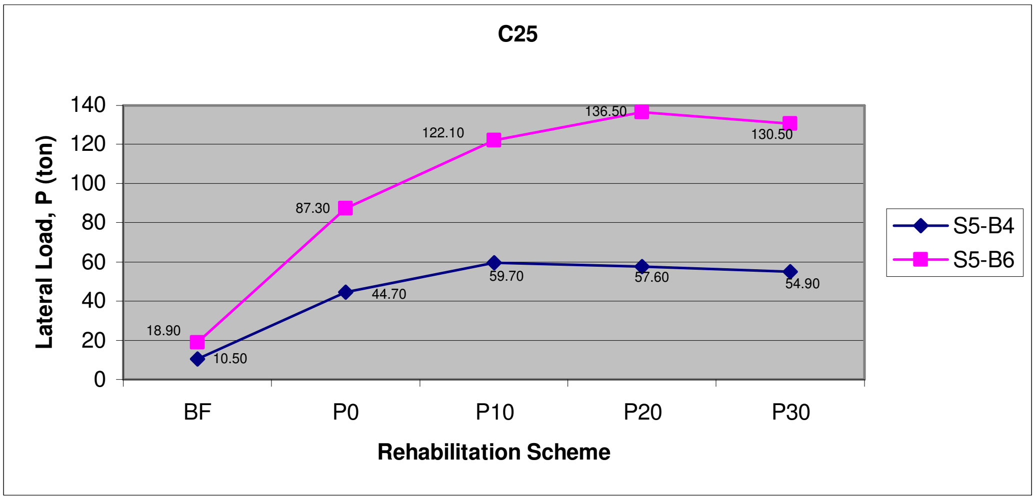


Figure 3.13: Effect of preloading on S5-B4 and S5-B6 frames for C25 concrete.

Figure 3.13 shows the effect of preloading for concrete compressive strength of $f_c^{'}$ = 25 MPa in S5-B4 and S5-B6 frame structures. It is seen that for S5-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 10.50 tons and it is increased up to 44.70 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 4.3 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 59.70, 57.60, and 54.90 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 5.7 times that of the Bare Frame.

For S5-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 18.90 tons and it is increased up to 87.30 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 4.6 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 122.10, 136.50, and 130.50 tons, respectively. The maximum lateral load capacity is reached at a preload level of 20% is approximately 7.2 times that of the Bare Frame.

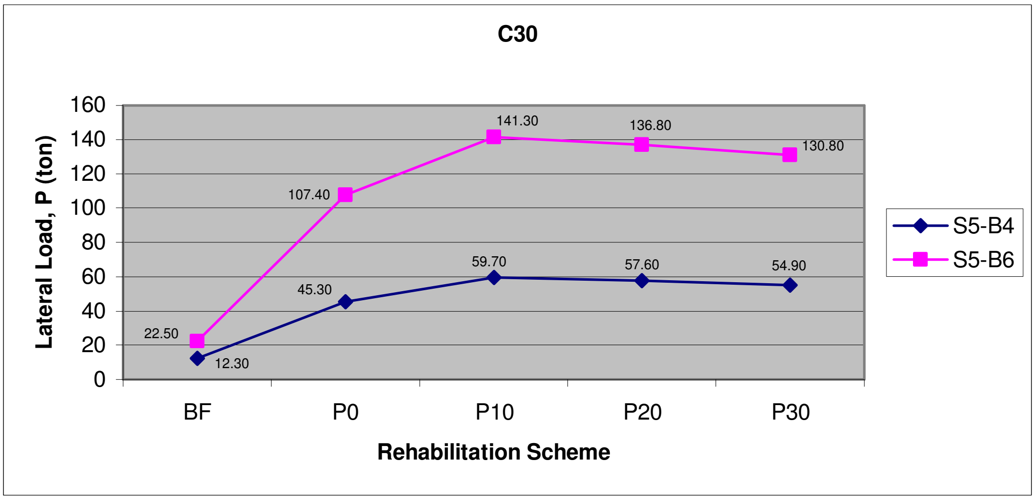


Figure 3.14: Effect of preloading on S5-B4 and S5-B6 frames for C30 concrete.

Figure 3.14 shows the effect of preloading for concrete compressive strength of $f_c^{'}$ = 30 MPa in S5-B4 and S5-B6 frame structures. It is seen that for S5-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 12.30 tons and it is increased up to 45.30 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 3.7 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 59.70, 57.60, and 54.90 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 4.9 times that of the Bare Frame.

For S5-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 22.50 tons and it is increased up to 107.40 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 4.8 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 141.30, 136.80, and 130.80 tons, respectively. The maximum lateral load capacity is reached at a preload level of 10% is approximately 6.3 times that of the Bare Frame.

The influence of preloading on the effectiveness of the rehabilitation schemes using closed-frame steel X-bracing for five-storey R/C frames is shown in Figures 3.15 and 3.16.

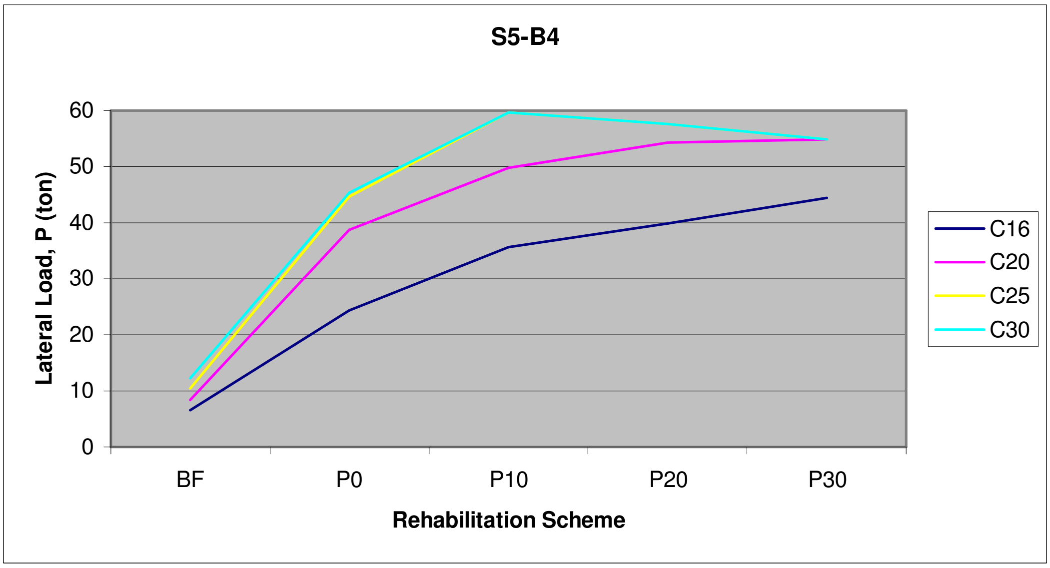


Figure 3.15: Influence of preloading on the lateral load capacity of S5-B4 frames.

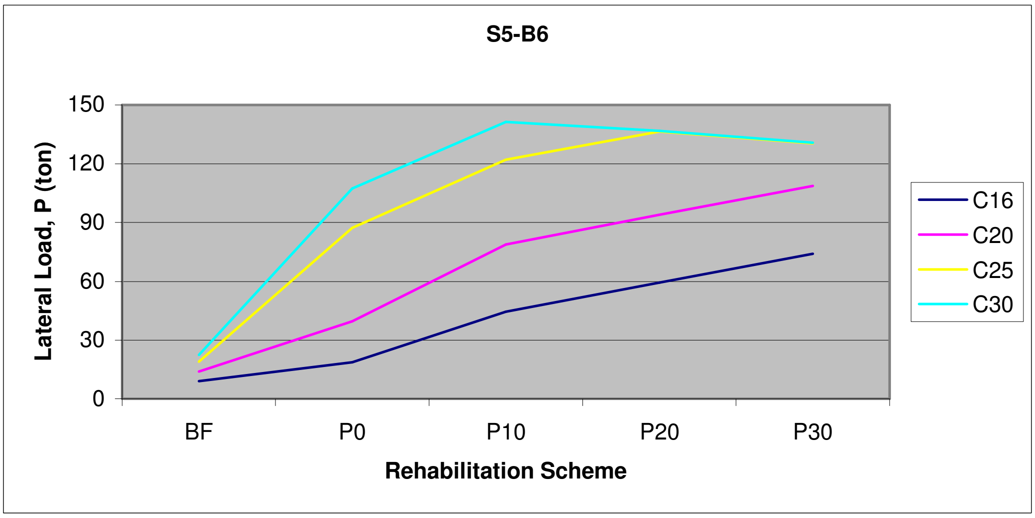


Figure 3.16: Influence of preloading on the lateral load capacity of S5-B6 frames.

3.2.3 Single-Bay Eight-Storey Frames

The analysis procedure of single-bay three-storey and single-bay five-storey reinforced concrete frame structures strengthened with steel closed-frame X-bracing scheme has been repeated for single-bay eight-storey reinforced concrete frame structures for the same concrete strength classes and the same preloading levels. The results are summarized below.

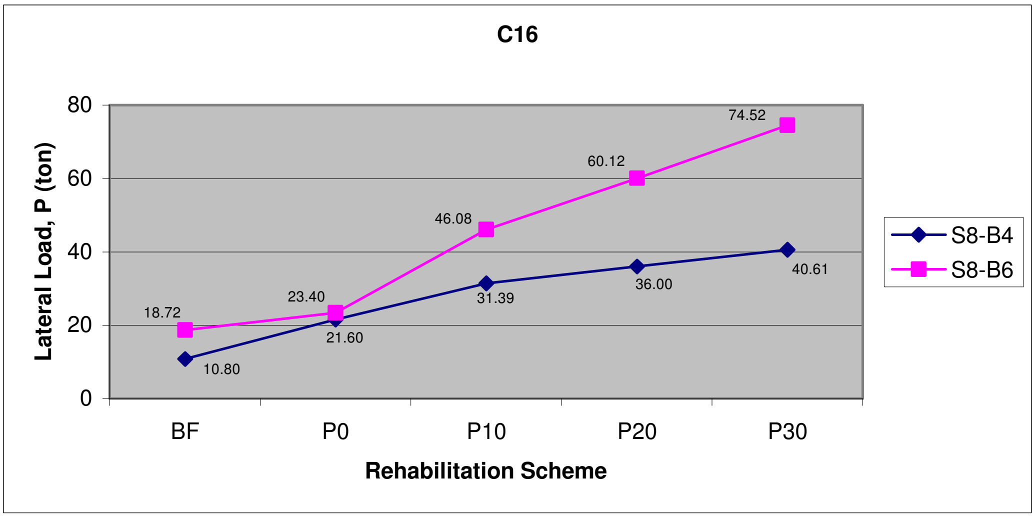


Figure 3.17: Effect of preloading on S8-B4 and S8-B6 frames for C16 concrete.

Figure 3.17 shows the effect of preloading for concrete compressive strength of $f_c^{'}$=16 MPa in S8-B4 and S8-B6 frame structures. It is seen that for S8-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 10.80 tons and it is increased up to 21.60 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 2.0 times that of the Bare Frame ultimate capacity. It is also evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 31.39, 36.00, and 40.61 tons, respectively. The maximum lateral load capacity reached at 30% preloading level is approximately 3.8 times that of the Bare Frame.

For S8-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 18.72 tons and it is increased up to 23.40 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 1.3 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 46.08, 60.12, and 74.52 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 4.0 times that of the initial Bare Frame.

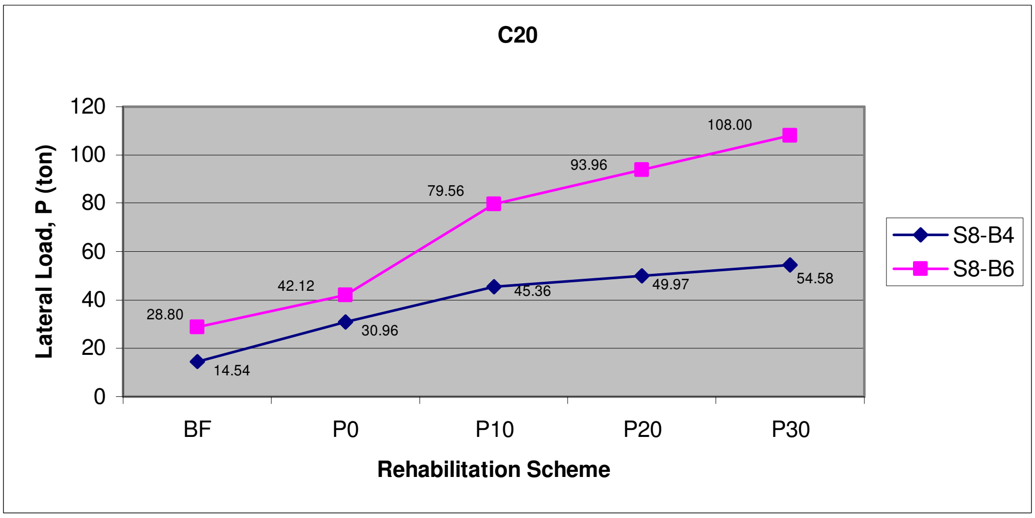


Figure 3.18: Effect of preloading on S8-B4 and S8-B6 frames for C20 concrete.

Figure 3.18 shows the effect of preloading for concrete compressive strength of $f_c^{'}$=20 MPa in S8-B4 and S8-B6 frame structures. It is seen that for S8-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 14.54 tons and it is increased up to 30.96 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 2.1 times that of the Bare Frame ultimate capacity. It is also evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 45.36, 49.97, and 54.58 tons, respectively. The maximum lateral load capacity reached at 30% preloading level is approximately 3.8 times that of the Bare Frame.

For S8-B6 structure the ultimate lateral load capacity of Bare Frame (**BF**) is 28.80 tons and it is increased up to 42.12 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 1.5 times that of the Bare Frame ultimate capacity. It is again evident that the lateral load capacity of the rehabilitated structure increases when a preloading is applied to the columns of the steel perimeter frame of the bracing system. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 79.56, 93.96, and 108.00 tons, respectively. The maximum lateral load capacity attained at a preloading level of 30% is approximately 3.8 times that of the initial Bare Frame.

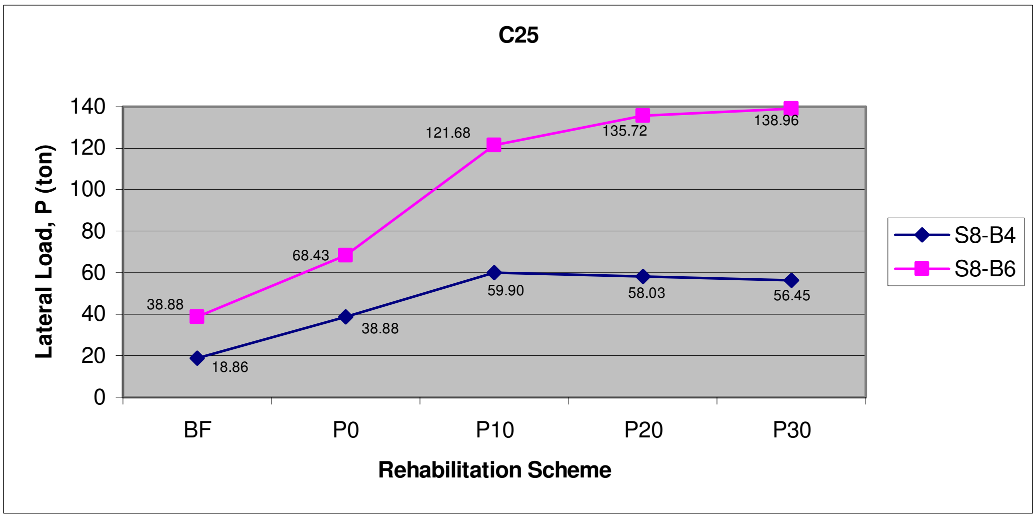


Figure 3.19: Effect of preloading on S8-B4 and S8-B6 frames for C25 concrete.

Figure 3.19 shows the effect of preloading for concrete compressive strength of $f_c' =$ 25 MPa in S8-B4 and S8-B6 frame structures. It is seen that for S8-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 18.86 tons and it is increased up to 38.88 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 2.1 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 59.90, 58.03, and 56.45 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 3.2 times that of the Bare Frame.

For S8-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 38.88 tons and it is increased up to 68.43 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 1.8 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 121.68, 135.72, and 138.96 tons, respectively. The maximum lateral load capacity is reached at a preload level of 30% is approximately 3.6 times that of the Bare Frame.

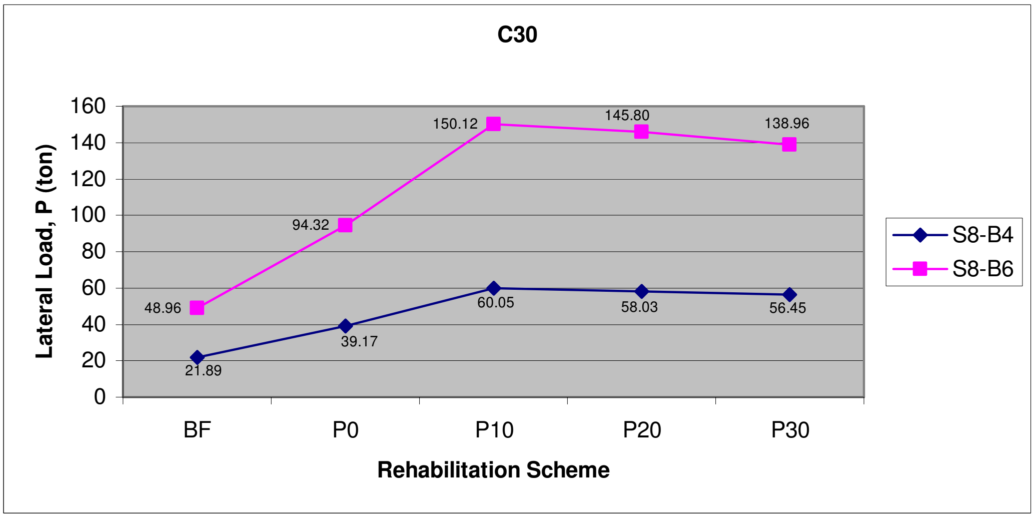


Figure 3.20: Effect of preloading on S8-B4 and S8-B6 frames for C30 concrete.

Figure 3.20 shows the effect of preloading for concrete compressive strength of $f_c' =$ 30 MPa in S8-B4 and S8-B6 frame structures. It is seen that for S8-B4 frame the ultimate lateral load capacity of Bare Frame (**BF**) is 21.89 tons and it is increased up to 39.17 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 1.8 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 60.05, 58.03, and 56.45 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 2.7 times that of the Bare Frame.

For S8-B6 frame structure the ultimate lateral load capacity of the Bare Frame (**BF**) is 48.96 tons and it is increased up to 94.32 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 1.9 times that of the Bare Frame ultimate capacity. With 10%, 20% and 30% preloading the ultimate lateral load capacity is increased to 150.12, 145.80, and 138.96 tons, respectively. The maximum lateral load capacity is reached at a preload level of 10% is approximately 3.1 times that of the Bare Frame.

The influence of preloading on the effectiveness of the rehabilitation schemes using closed-frame steel X-bracing for eight-storey R/C frames is shown in Figures 3.21 and 3.22.

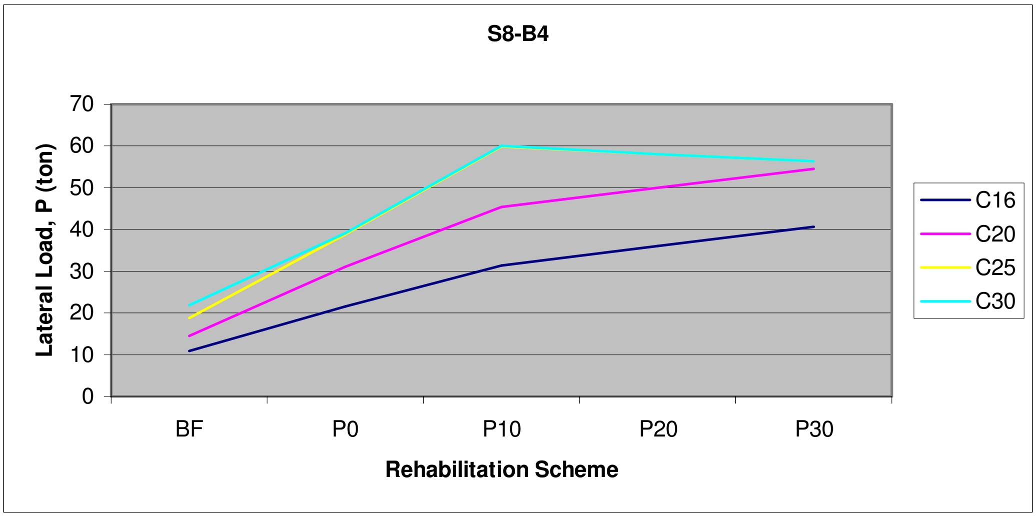


Figure 3.21: Influence of preloading on the lateral load capacity of S8-B4 frames.

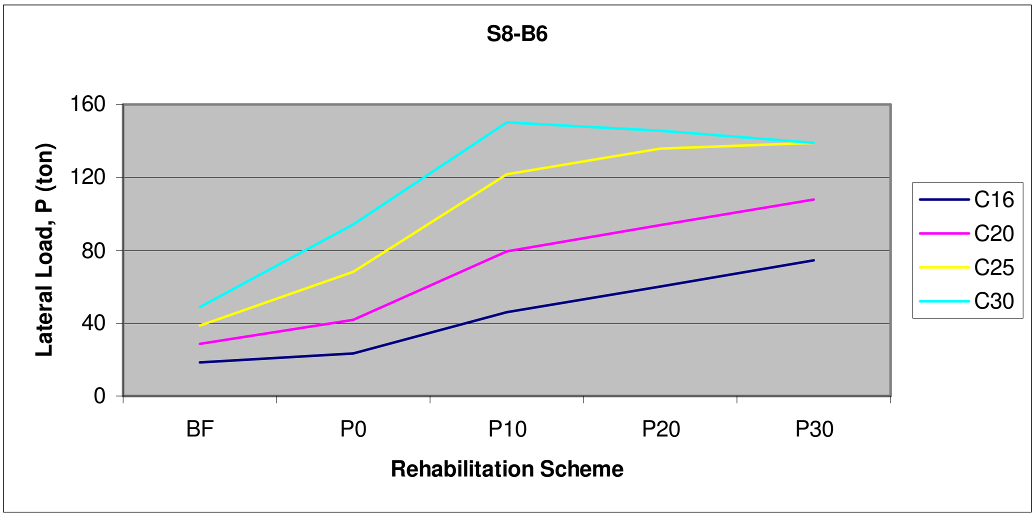


Figure 3.22: Influence of preloading on the lateral load capacity of S8-B6 frames.

3.2.4 Two-Bay Three-Storey Frames

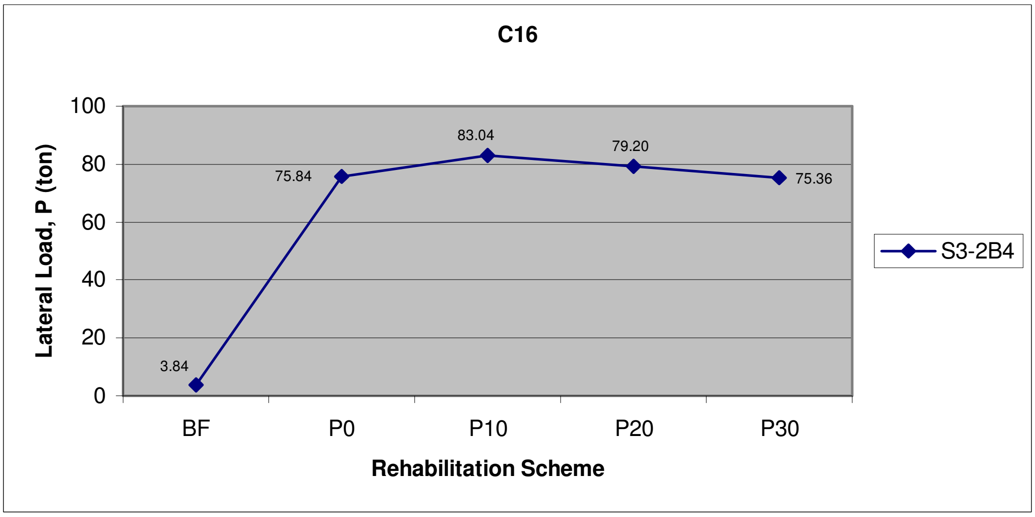


Figure 3.23: Effect of preloading on S3-2B4 frame for C16 concrete.

Figure 3.23 shows the effect of preloading for concrete compressive strength of $f_c^{'}$ = 16 MPa in S3-2B4 frame structure. It is seen that the ultimate lateral load capacity of Bare Frame (**BF**) is 3.84 tons and it is increased up to 75.84 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 19.8 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 83.04, 79.20, and 75.36 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 21.6 times that of the Bare Frame.

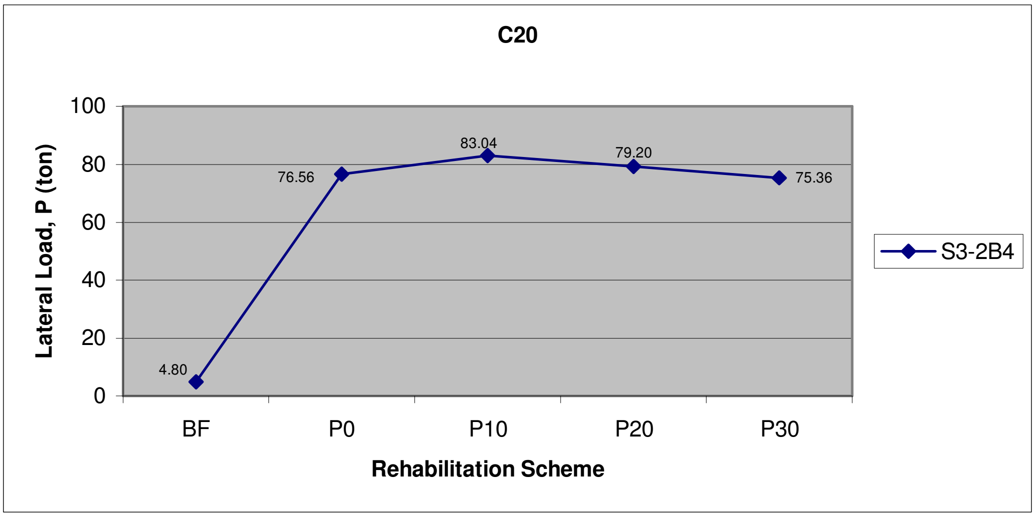


Figure 3.24: Effect of preloading on S3-2B4 frame for C20 concrete.

Figure 3.24 shows the effect of preloading for concrete compressive strength of $f_c' =$ 20 MPa in S3-2B4 frame structure. It is seen that the ultimate lateral load capacity of Bare Frame (**BF**) is 4.80 tons and it is increased up to 76.56 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 16.0 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 83.04, 79.20, and 75.36 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 17.3 times that of the Bare Frame.

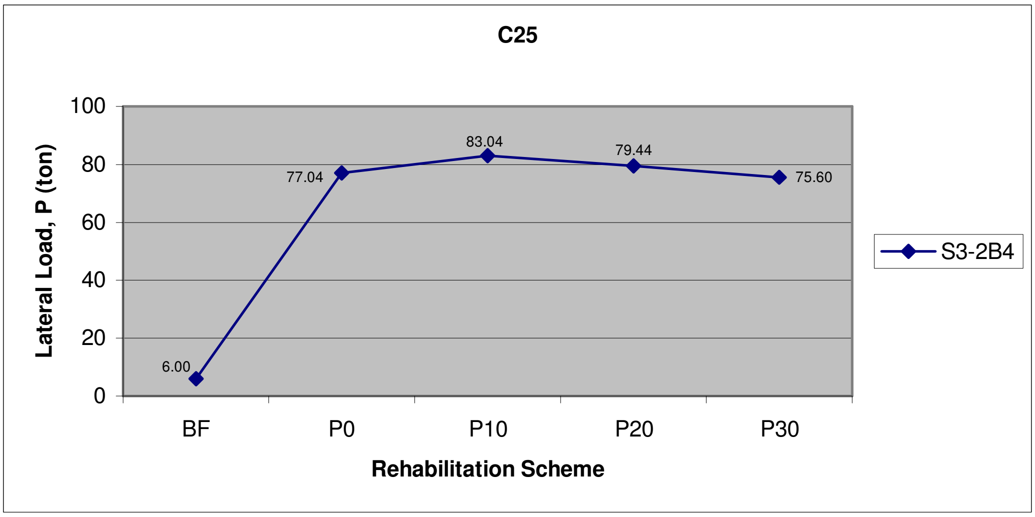


Figure 3.25: Effect of preloading on S3-2B4 frame for C25 concrete.

Figure 3.25 shows the effect of preloading for concrete compressive strength of $f_c' =$ 25 MPa in S3-2B4 frame structure. It is seen that the ultimate lateral load capacity of Bare Frame (**BF**) is 6.00 tons and it is increased up to 77.04 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 12.8 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 83.04, 79.44, and 75.60 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 13.8 times that of the Bare Frame.

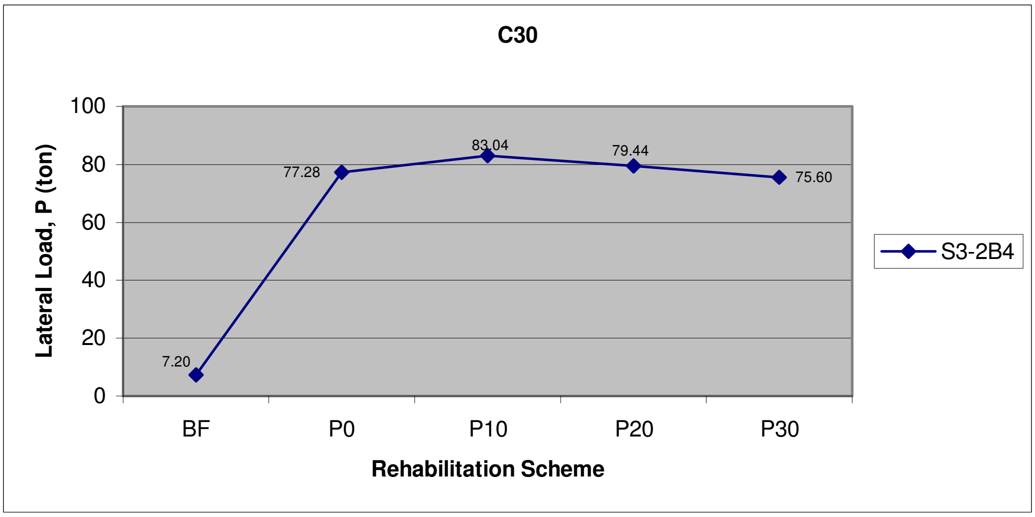


Figure 3.26: Effect of preloading on S3-2B4 frame for C30 concrete.

Figure 3.26 shows the effect of preloading for concrete compressive strength of $f_c^{'}$ = 30 MPa in S3-2B4 frame structure. It is seen that the ultimate lateral load capacity of Bare Frame (**BF**) is 7.20 tons and it is increased up to 77.28 tons with closed-frame X-bracing strengthening scheme without preloading (**P0**). This is approximately 10.7 times that of the Bare Frame ultimate capacity. A gradually decreasing trend is observed in the lateral load capacity of the rehabilitated structures with the increasing preloading applied to the columns of the steel perimeter frame of the bracing system. But at 10% preloading situation (**P10**) the capacity is increased. With 10%, 20% and 30% preloading (**P10**, **P20,** and **P30**) the ultimate lateral load capacity is increased to 83.04, 79.44, and 75.60 tons, respectively. The maximum lateral load capacity reached at a preload level of 10% is approximately 11.5 times that of the Bare Frame.

The influence of preloading on the effectiveness of the rehabilitation schemes using closed-frame steel X-bracing for three-storey R/C frames is shown in Figure 3.27.

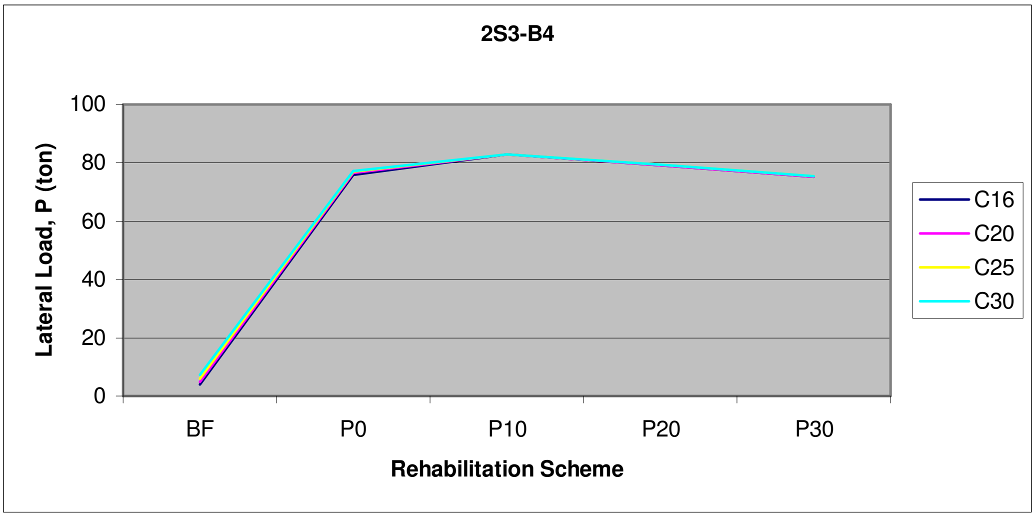


Figure 3.27: Influence of preloading on the lateral load capacity of S3-2B4 frames.

3.3 Relative Results of Frames Strengthened by Steel X-Bracing Enclosed with Steel Edge Members

3.3.1 Relative Results of Frames with 4m Span Length

The maximum capacity increments of the frames with four meter span length according to Bare Frame capacity of each frame separately (S3-B4, S5-B4 and S8-B4) are given in the Figure 3.28.

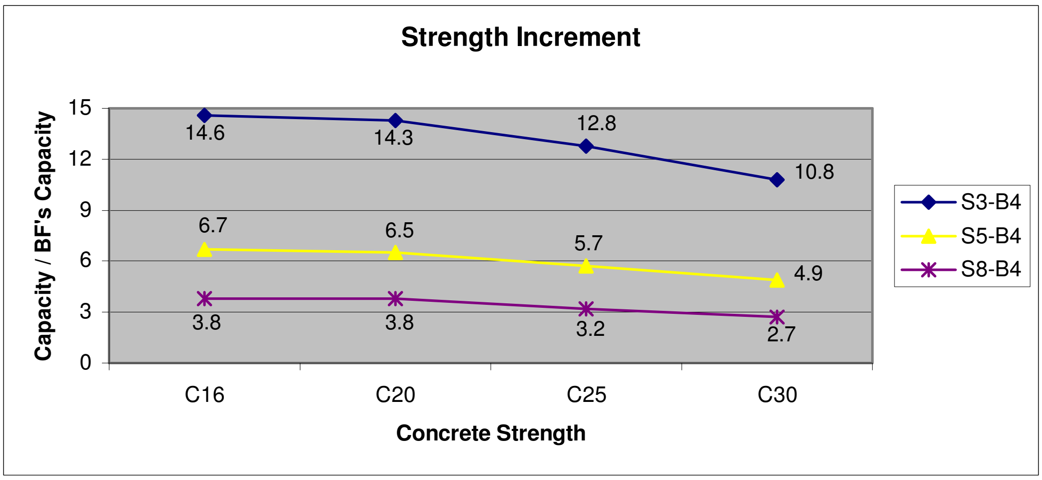


Figure 3.28: Strength increment of frames with 4m span length.

As it is seen from the Figure 3.28 the ultimate lateral load capacity increments of the frames with closed-frame X-bracing strengthening scheme with four meter span length according to each case's Bare Frame's capacity decrease with the increasing number of story. This is due to the increasing overturning moment. When the story number increases, the same lateral load makes more overturning moment. And when the amount of overturning moment increases, the columns can resist less axial forces.

For each preloading rate (0%, 10%, 20% and 30% preloading) the capacity increments of the frames with four meter span length according to Bare Frame capacity of each frame separately are given in Figure 3.29, 3.30, 3.31 and 3.32.

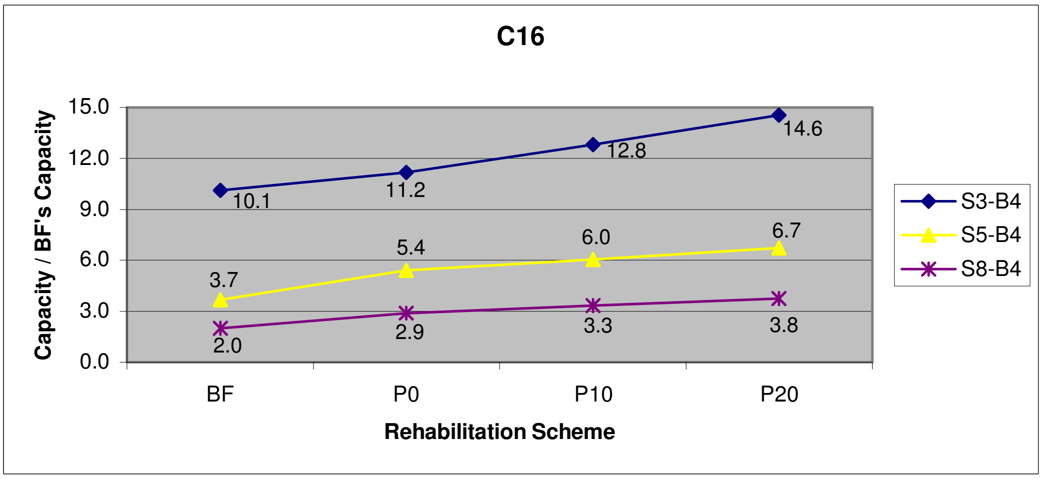


Figure 3.29: Strength increments of frames with 4m span length for C16 concrete.

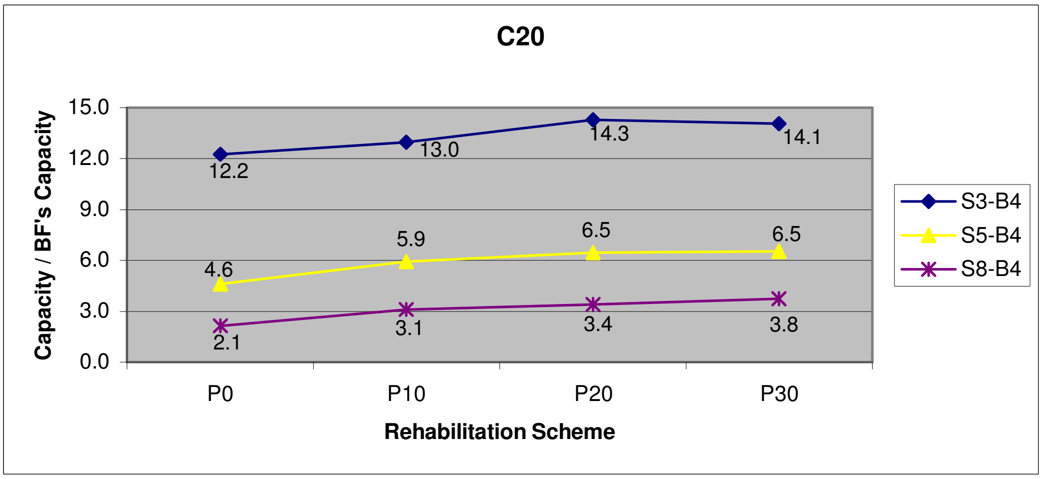


Figure 3.30: Strength increments of frames with 4m span length for C20 concrete.

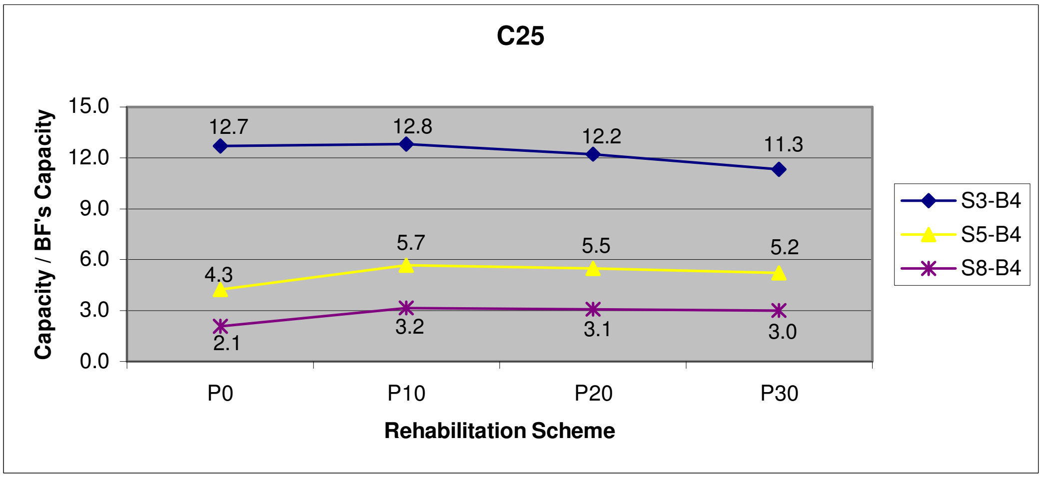


Figure 3.31: Strength increments of frames with 4m span length for C25 concrete.

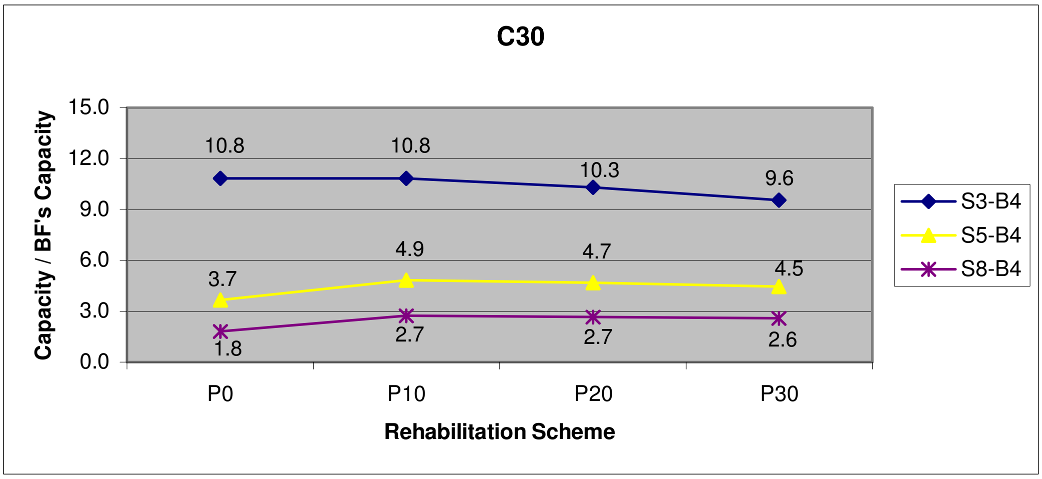


Figure 3.32: Strength increments of frames with 4m span length for C30 concrete.

3.3.2 Relative Results of Frames with 6m Span Length

The maximum capacity increments of the frames with six meter span length according to Bare Frame capacity of each case separately (S3-B6, S5-B6 and S8-B6) are given in the Figure 3.33.

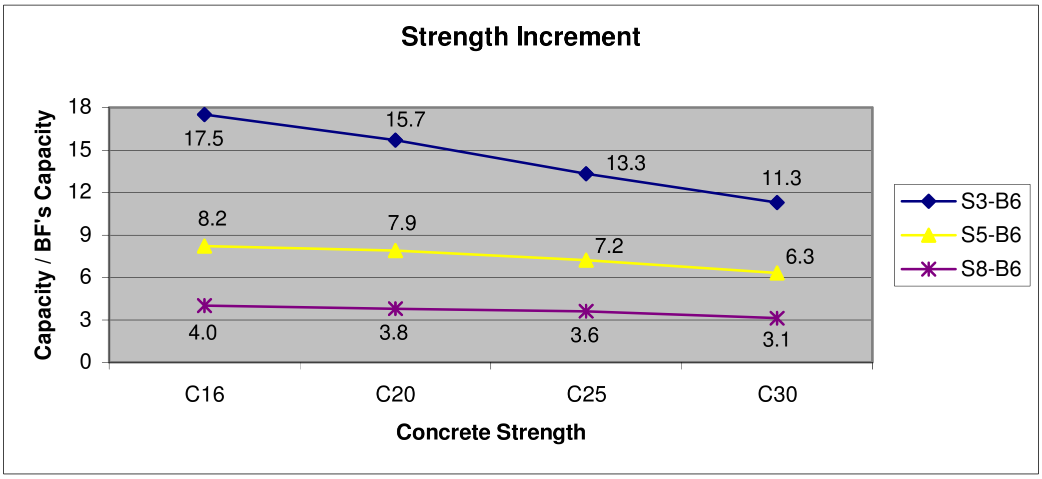


Figure 3.33: Strength increment of frames with 6m span length.

As it is seen from the Figure 3.33 the ultimate lateral load capacity increments of the full member rehabilitated frames with six meter span length according to each case's Bare Frame's capacity decrease with the increasing number of story.

For each preloading rate (0%, 10%, 20% and 30% preloading) the capacity increments of the frames with six meter span length according to Bare Frame capacity of each frame separately are given in Figure 3.34, 3.35, 3.36 and 3.37.

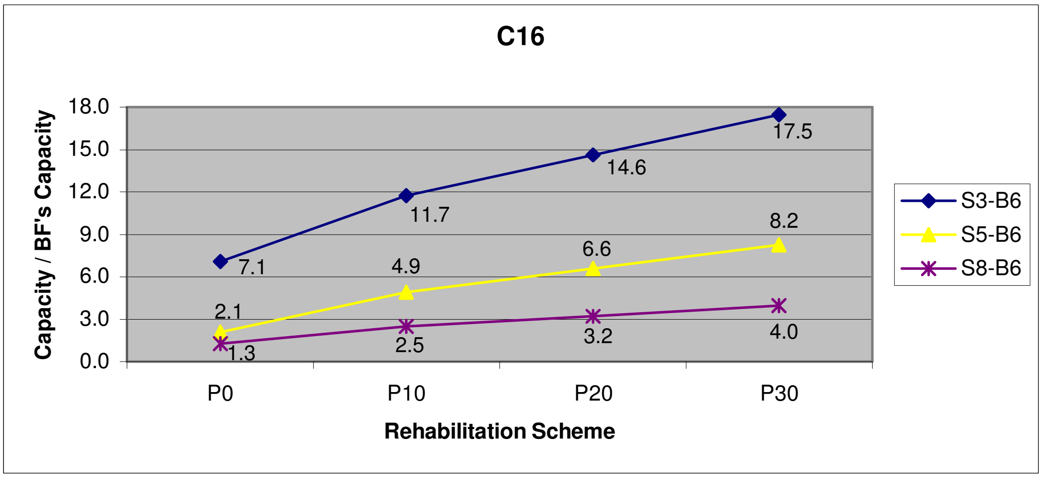


Figure 3.34: Strength increments of frames with 6m span length for C16 concrete.

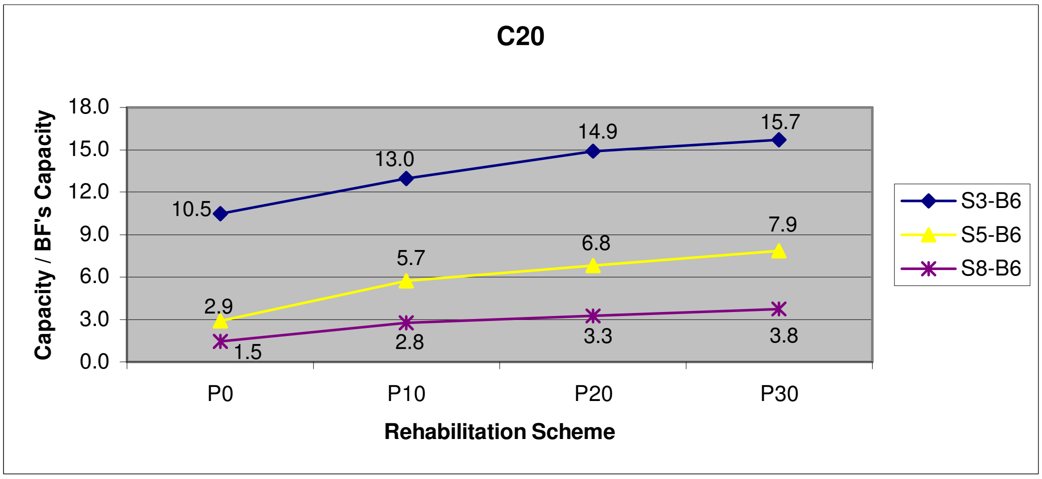


Figure 3.35: Strength increments of frames with 6m span length for C20 concrete.

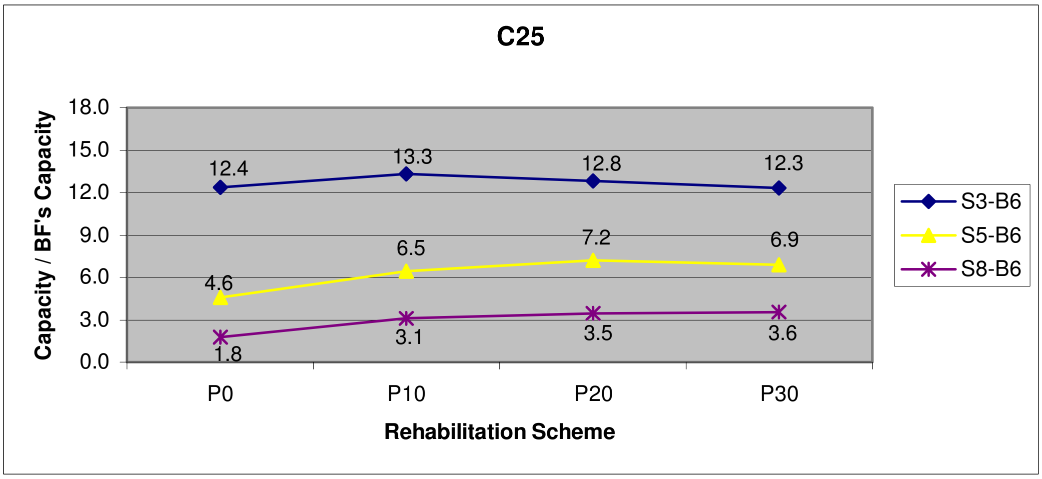


Figure 3.36: Strength increments of frames with 6m span length for C25 concrete.

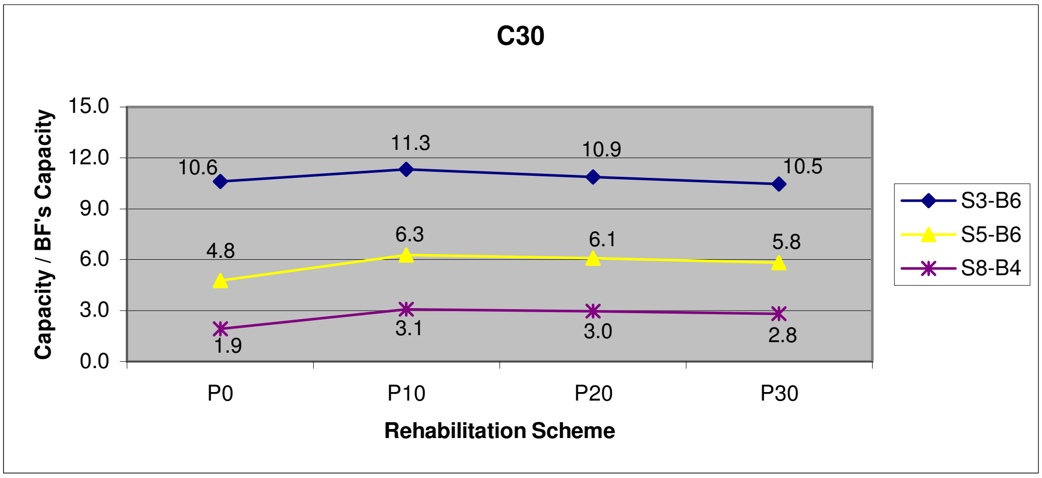


Figure 3.37: Strength increments of frames with 6m span length for C30 concrete.

3.3.3 Relative Results of Frames with 2x4m Span Lengths

The capacity increment of the frame with 2x4 meter span lengths according to Bare Frame capacity (S3-2B4) is given in the Figure 3.38.

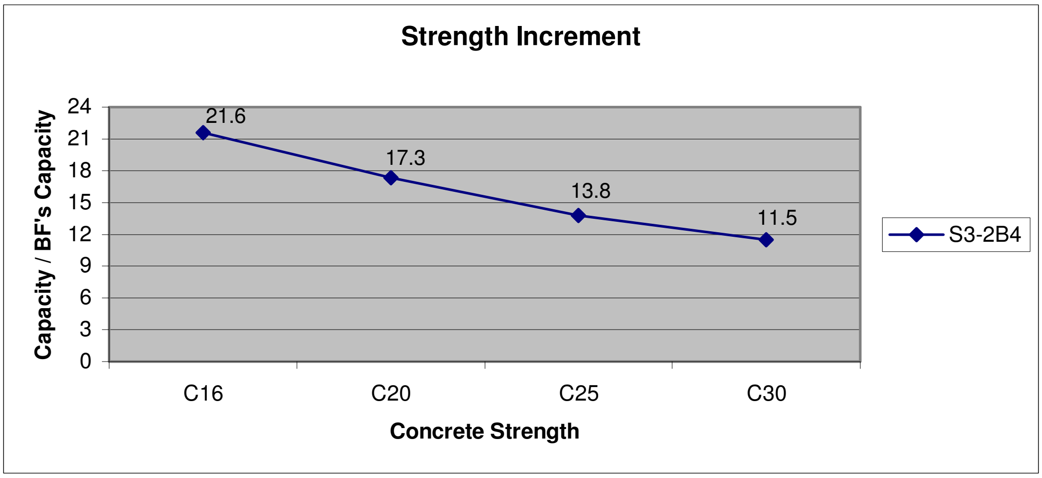


Figure 3.38: Strength increment of frames with 2x4m span lengths.

For each preloading rate (0%, 10%, 20% and 30% preloading) the capacity increments of the frames with 2x4 meter span lengths according to Bare Frame capacity are given in Figure 3.39, 3.40, 3.41 and 3.42.

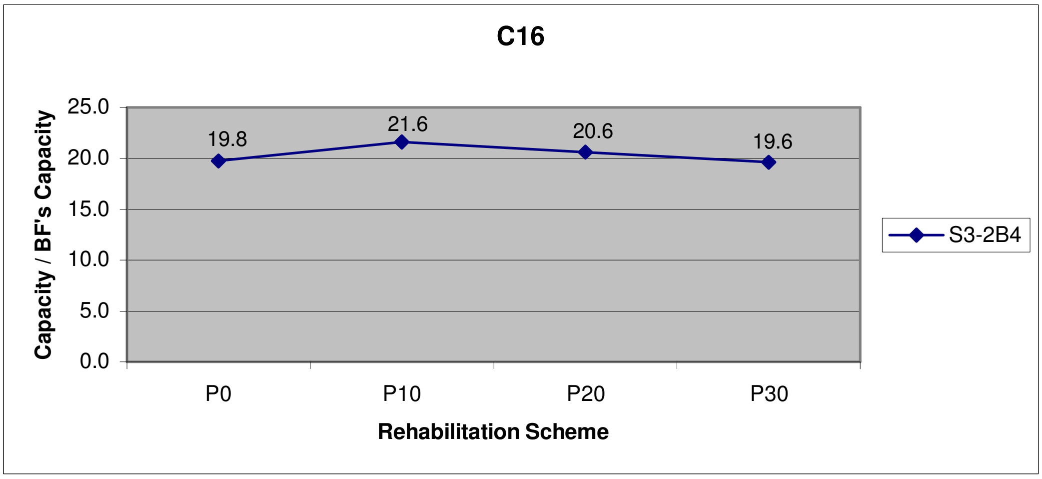


Figure 3.39: Strength increments of frames with 2x4m span lengths for C16 concrete.

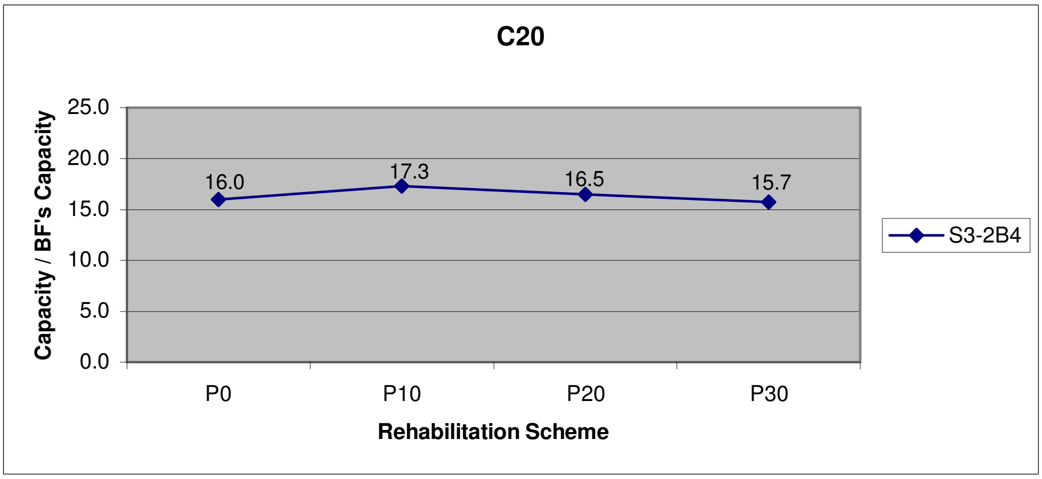


Figure 3.40: Strength increments of frames with 2x4m span lengths for C20 concrete.

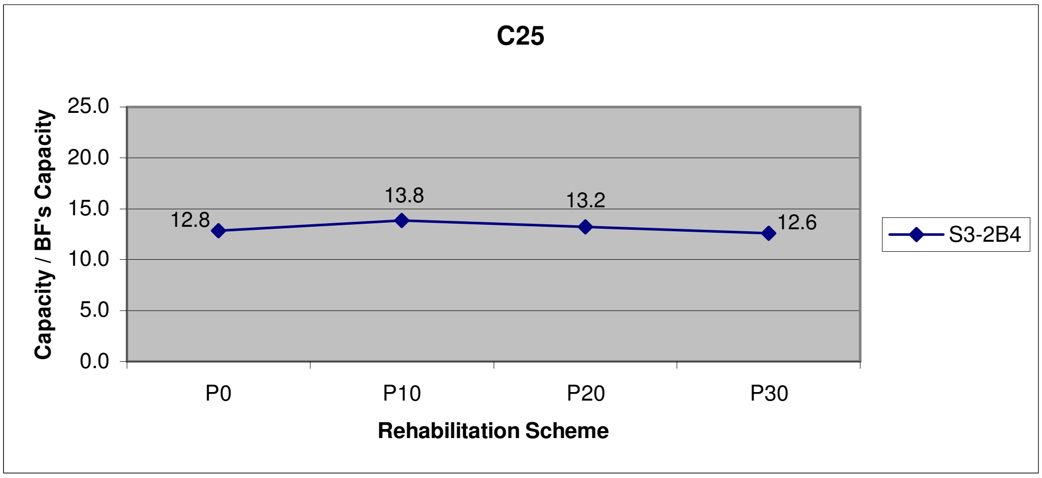


Figure 3.41: Strength increments of frames with 2x4m span lengths for C25 concrete.

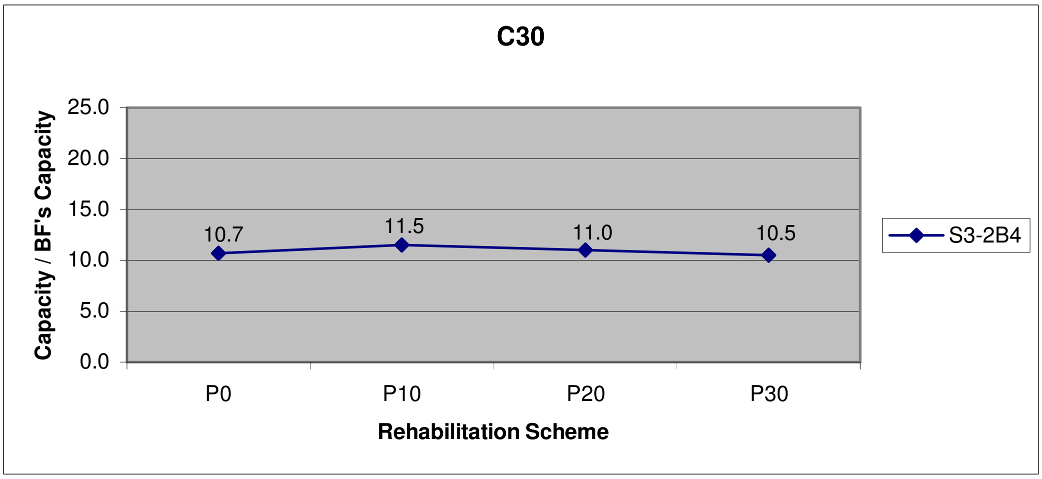


Figure 3.42: Strength increments of frames with 2x4m span lengths for C30 concrete.

3.4 Effect of Steel Beam Members in Ultimate Lateral Load Capacity

As it is mentioned, the difference between rehabilitation schemes of **P0** and **NB** is that the steel beam members are not used in rehabilitation scheme of **NB**. The aim of this scheme is to determine the effect of steel beam members on the behavior of the strengthened reinforced concrete frame.

3.4.1 Effect of Steel Beam Members in Ultimate Load Capacity for Frames with 4m Span Length

The capacity increments of the frames with four meter span length for rehabilitation schemes of **P0** and **NB** are shown in Figure 3.43, 3.44, 3.45 and 3.46.

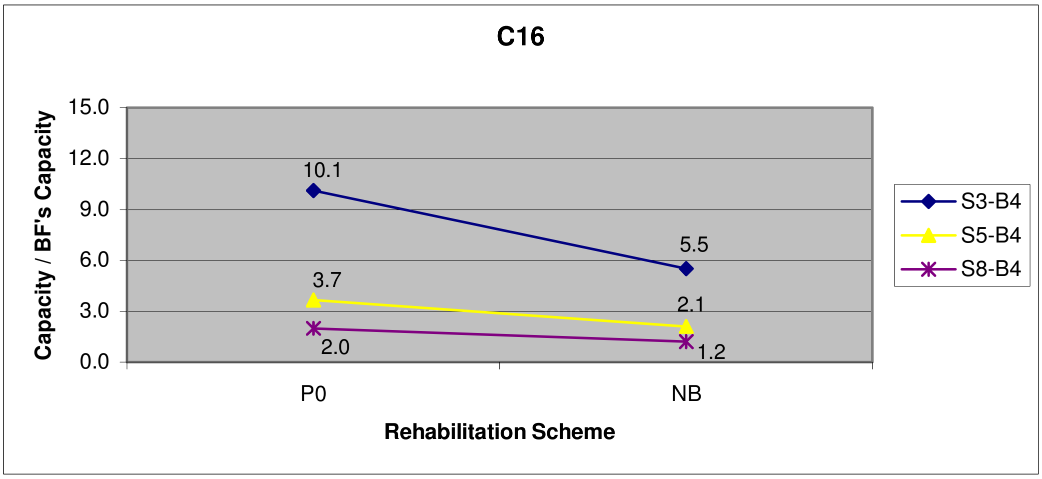


Figure 3.43: Strength increments of frames with 4m span length for C16 concrete.

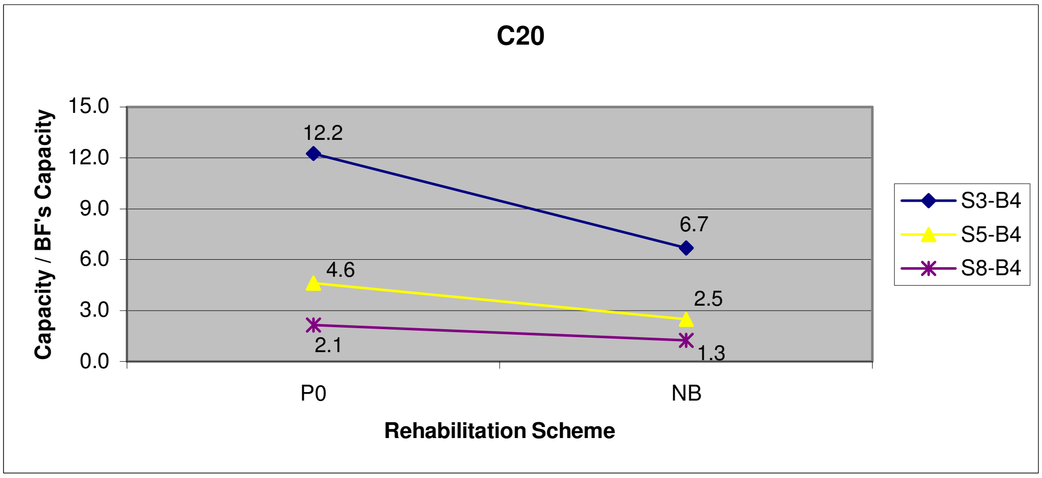


Figure 3.44: Strength increments of frames with 4m span length for C20 concrete.

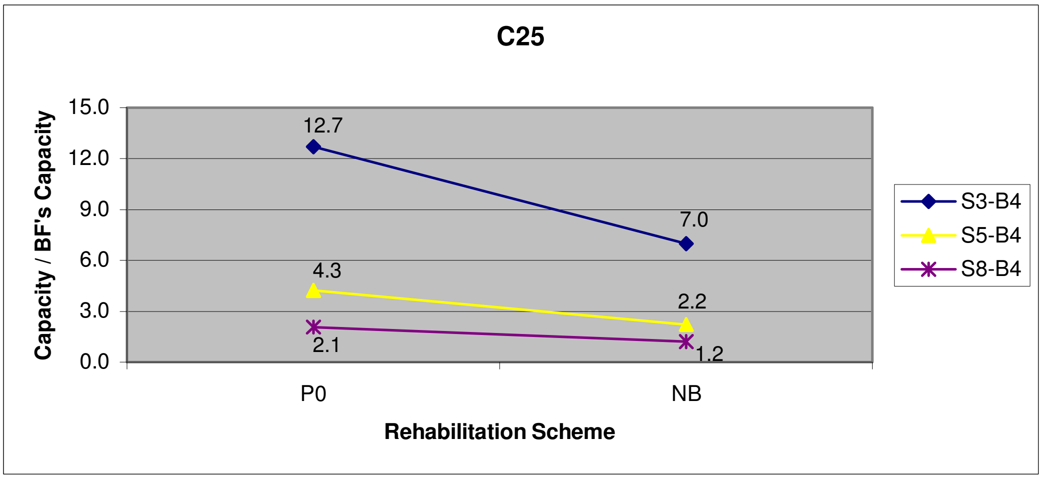


Figure 3.45: Strength increments of frames with 4m span length for C25 concrete.

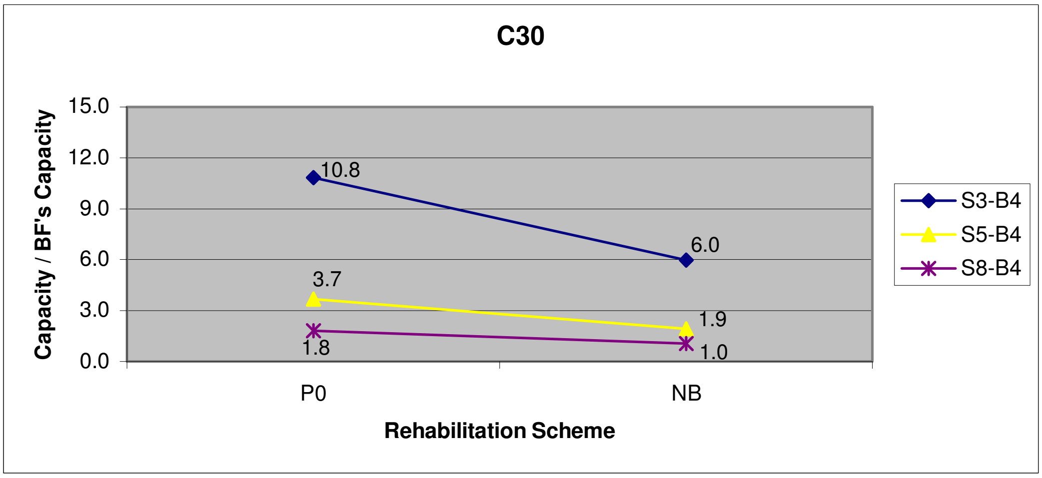


Figure 3.46: Strength increments of frames with 4m span length for C30 concrete.

As it is seen from the figures the ultimate lateral load capacity of the rehabilitated frames decreased when the steel beam members are not used.

3.4.2 Effect of Steel Beam Members in Ultimate Load Capacity for Frames with 6m Span Length

The capacity increments of the frames with six meter span length for rehabilitation schemes of **P0** and **NB** are shown in Figure 3.47, 3.48, 3.49 and 3.50.

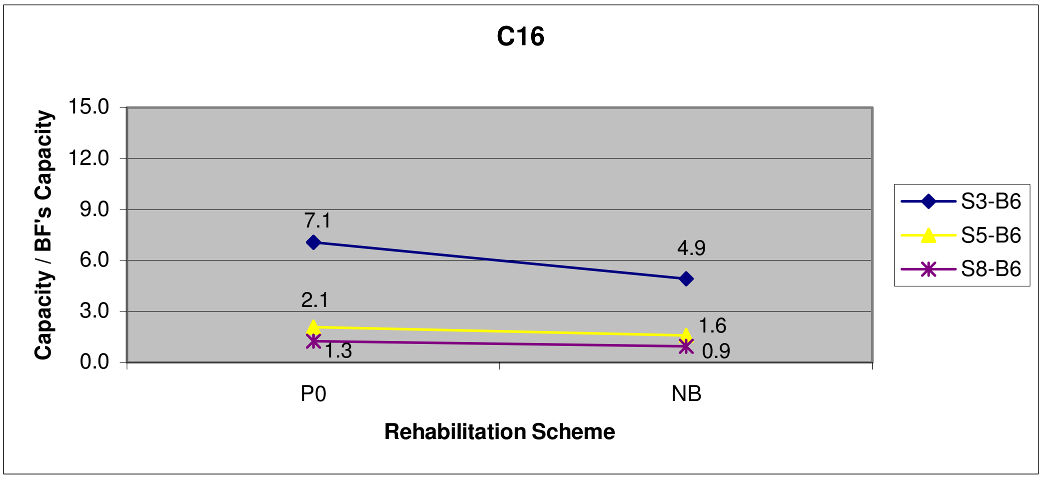


Figure 3.47: Strength increments of frames with 6m span length for C16 concrete.

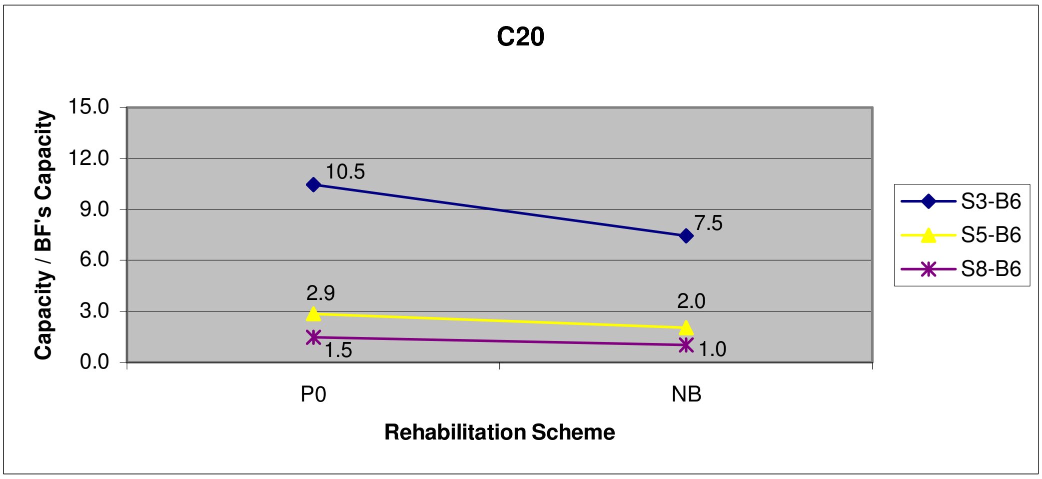


Figure 3.48: Strength increments of frames with 6m span length for C20 concrete.

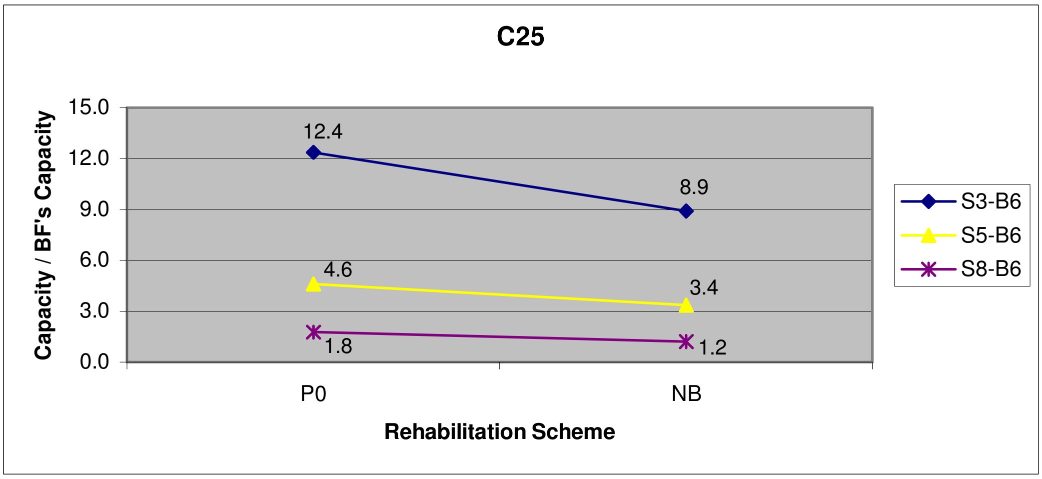


Figure 3.49: Strength increments of frames with 6m span length for C25 concrete.

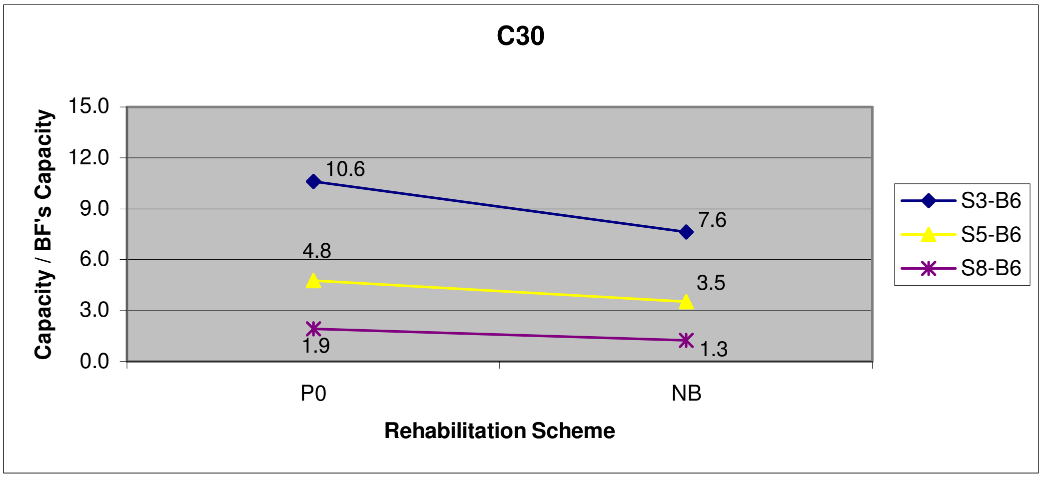


Figure 3.50: Strength increments of frames with 6m span length for C30 concrete.

3.4.3 Effect of Steel Beam Members in Ultimate Load Capacity for Frames with 2x4m Span Lengths

The capacity increments of the frames with 2x4 meter span lengths for rehabilitation schemes of **P0** and **NB** are shown in Figure 3.51, 3.52, 3.53 and 3.54.

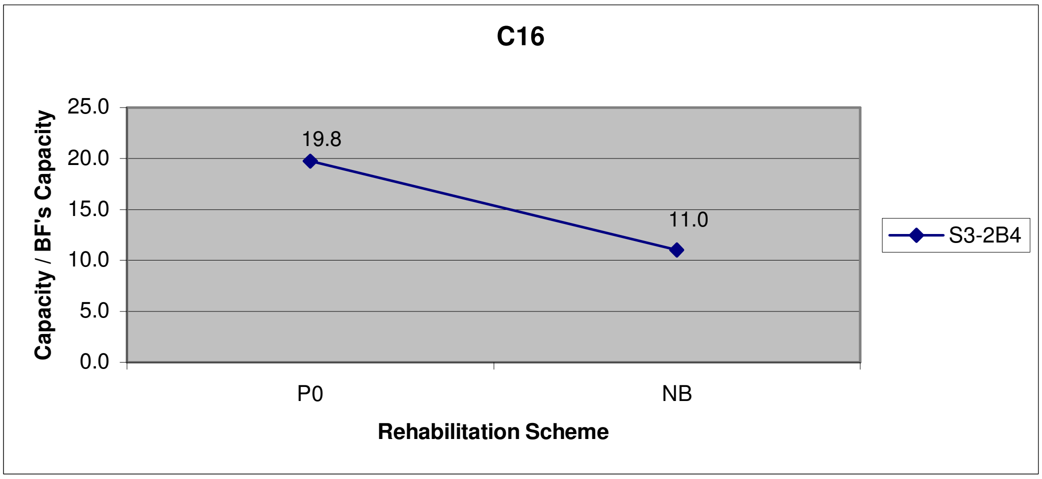


Figure 3.51: Strength increments of frames with 2x4m span lengths for C16 concrete.

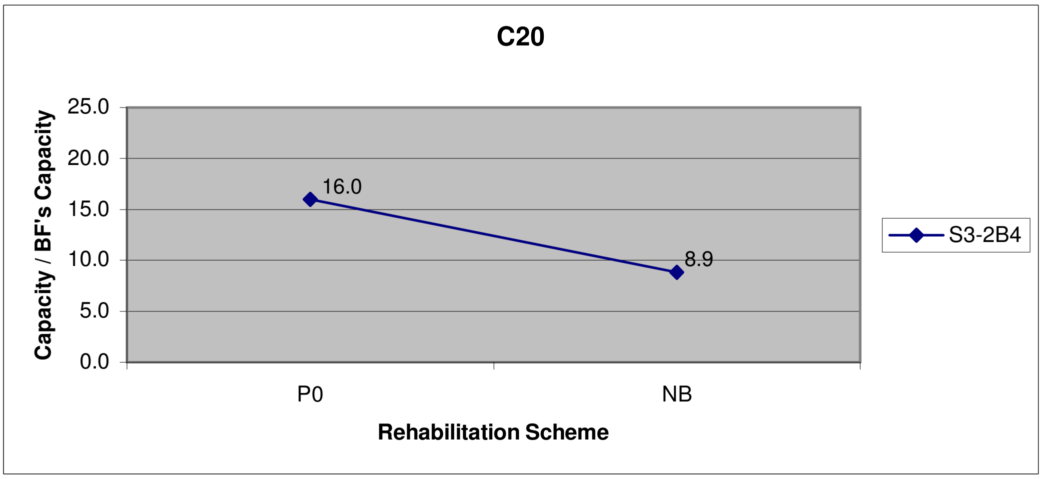


Figure 3.52: Strength increments of frames with 2x4m span lengths for C20 concrete.

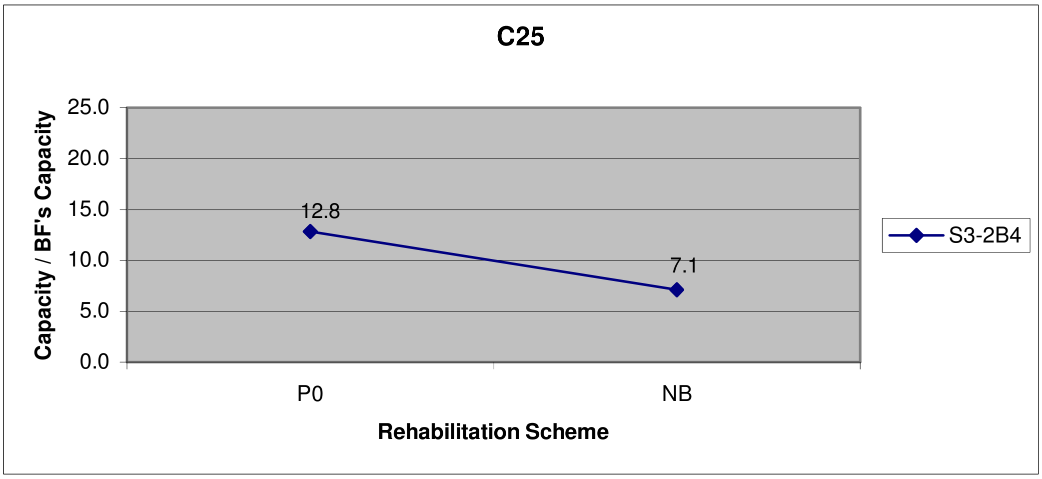


Figure 3.53: Strength increments of frames with 2x4m span lengths for C25 concrete.

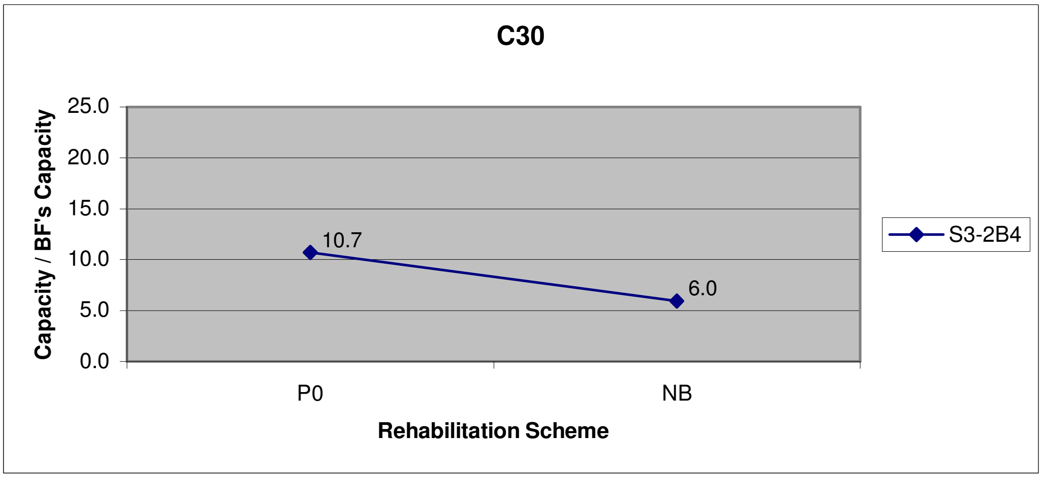


Figure 3.54: Strength increments of frames with 2x4m span lengths for C30 concrete.

3.5 Results of the Schemes Rehabilitated with Steel Bracing Members

As it is mentioned, there are some differences between rehabilitation schemes of **WA**, **UA** and **SUA**. Unlike from the rehabilitation scheme of **WA**, rehabilitation schemes of **UA** and **SUA** have the steel bracing members with no-tension property. So the aim is to determine the effect of connection between steel bracing members and reinforced concrete frame at the beam-column joints. It can be seen the results of connected and not connected bracings to the reinforced concrete frame in the rehabilitation schemes of **WA** and **UA** respectively. Sections of the steel bracing members in rehabilitation schemes of **WA** and **UA** have the same but in rehabilitation scheme of **SUA** section of the steel bracing members are increased to learn that how much the capacity of the frame can be increased.

3.5.1 Results of the Schemes Rehabilitated with Steel Bracing Members for Frames with 4m span length

The relative capacities of rehabilitation schemes for frames with four meter span length according to Bare Frame capacity of each case separately are shown in Figure 3.55, 3.56, 3.57 and 3.58.

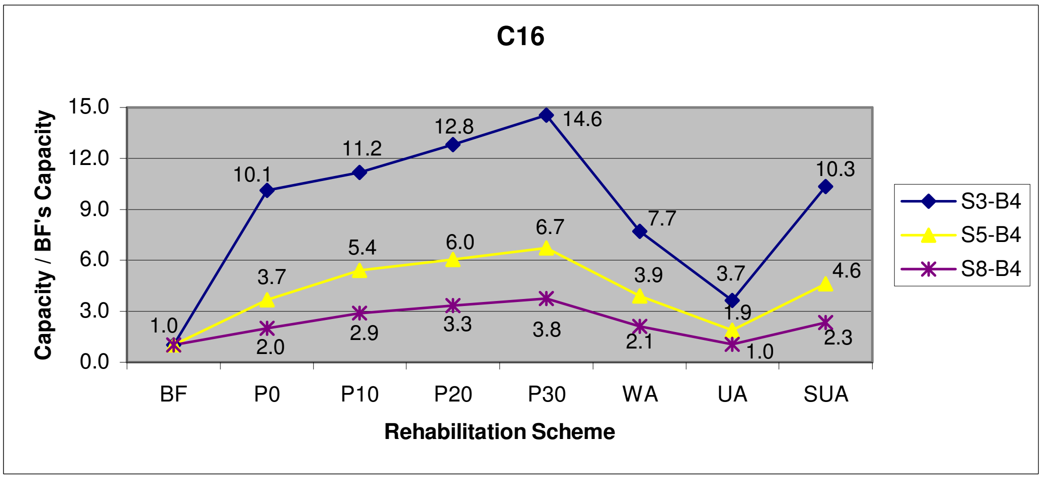


Figure 3.55: Strength increments of frames with 4m span length for C16 concrete.

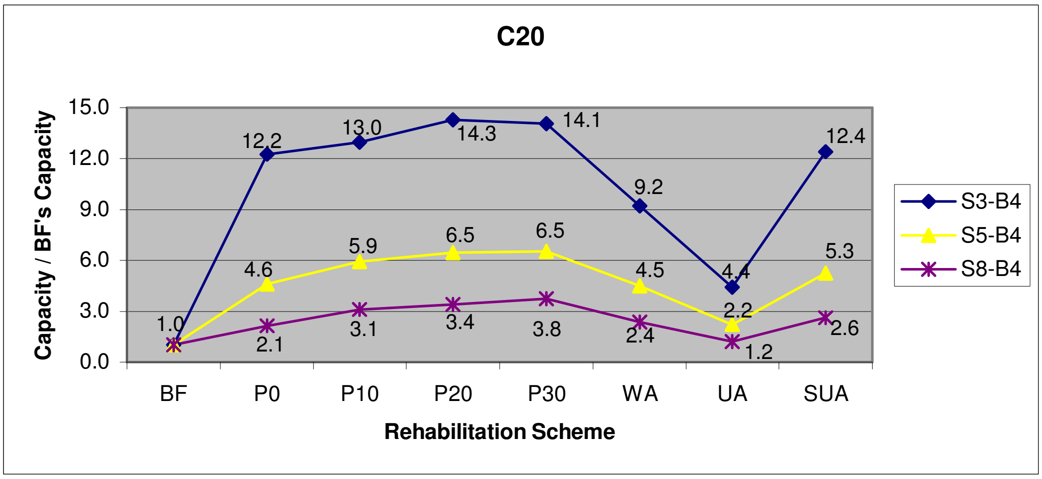


Figure 3.56: Strength increments of frames with 4m span length for C20 concrete.

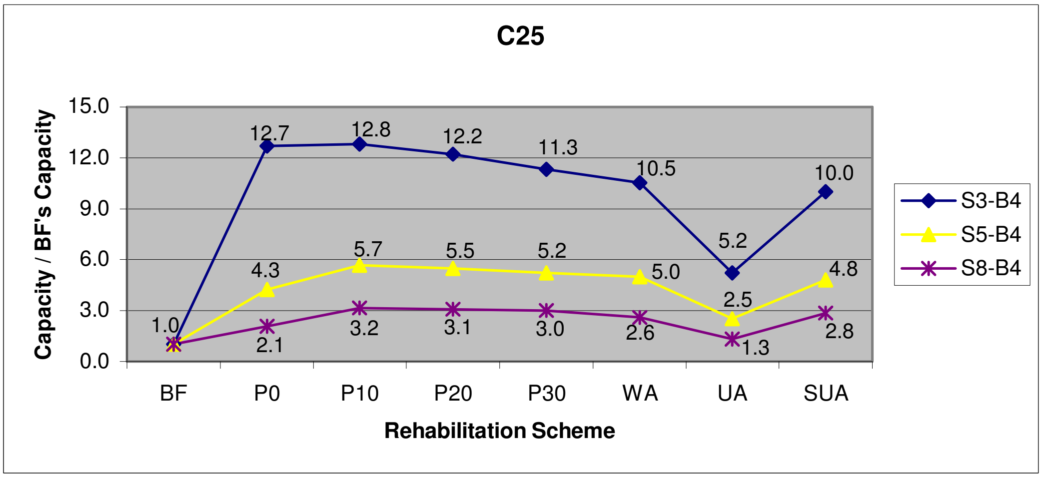


Figure 3.57: Strength increments of frames with 4m span length for C25 concrete.

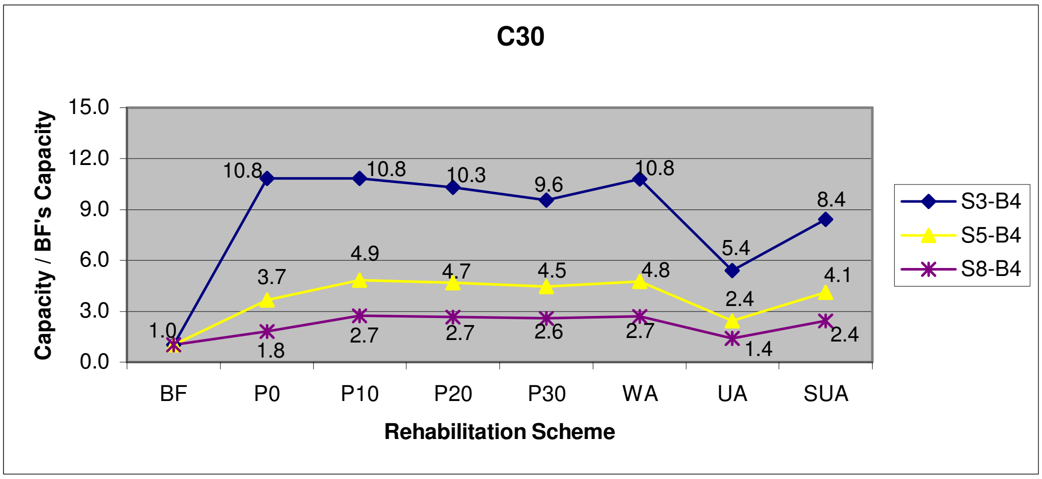


Figure 3.58: Strength increments of frames with 4m span length for C30 concrete.

3.5.2 Results of the Schemes Rehabilitated with Steel Bracing Members for frame with 6m span length

The relative capacities of rehabilitation schemes for frames with six meter span length according to Bare Frame capacity of each case separately are shown in Figure 3.59, 3.60, 3.61 and 3.62.

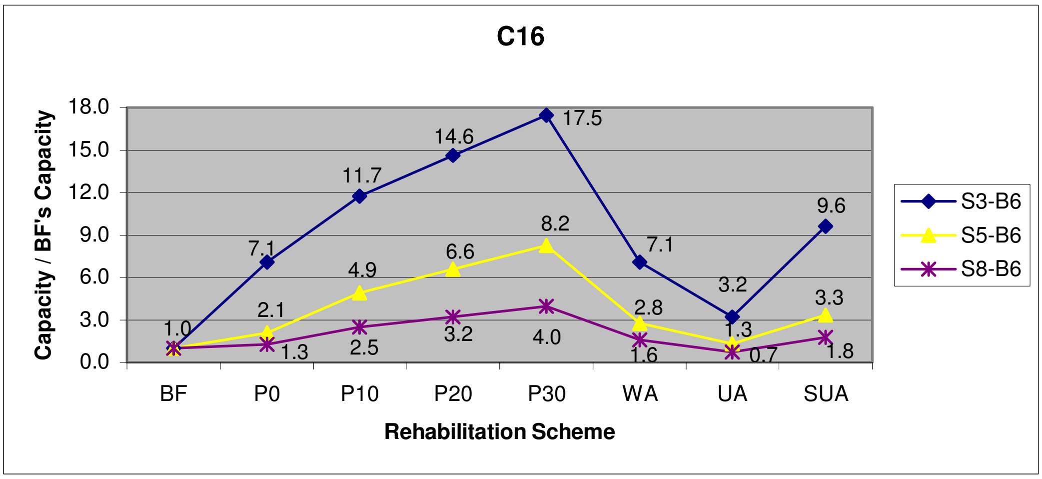


Figure 3.59: Strength increments of frames with 6m span length for C16 concrete.

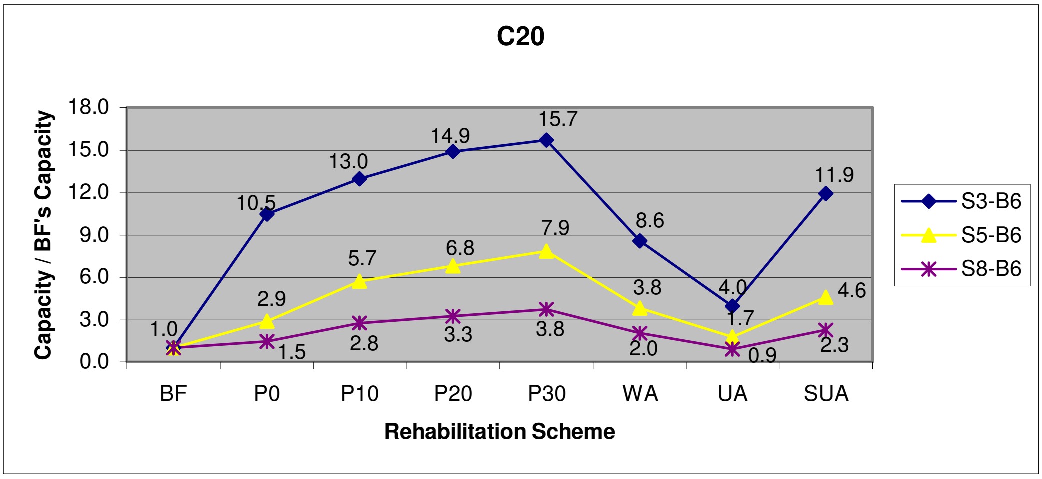


Figure 3.60: Strength increments of frames with 6m span length for C20 concrete.

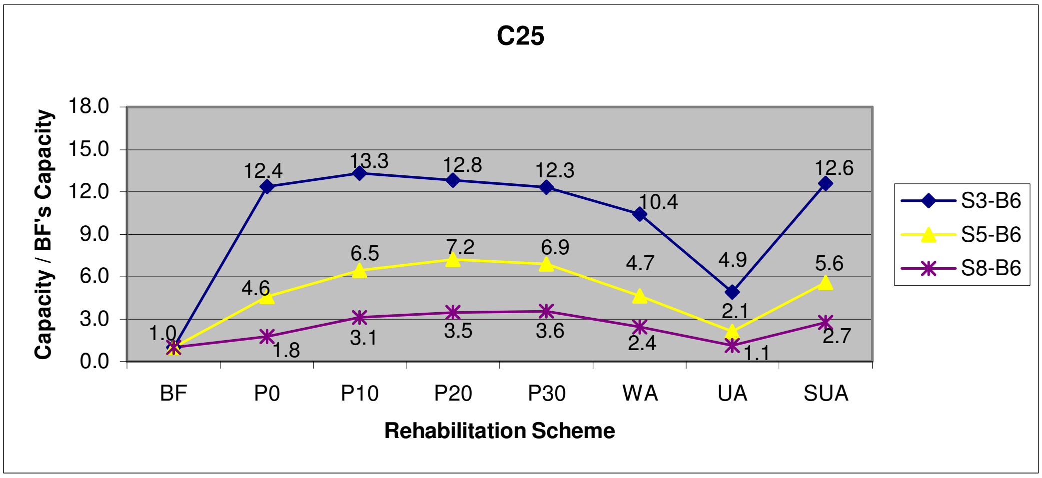


Figure 3.61: Strength increments of frames with 6m span length for C25 concrete.

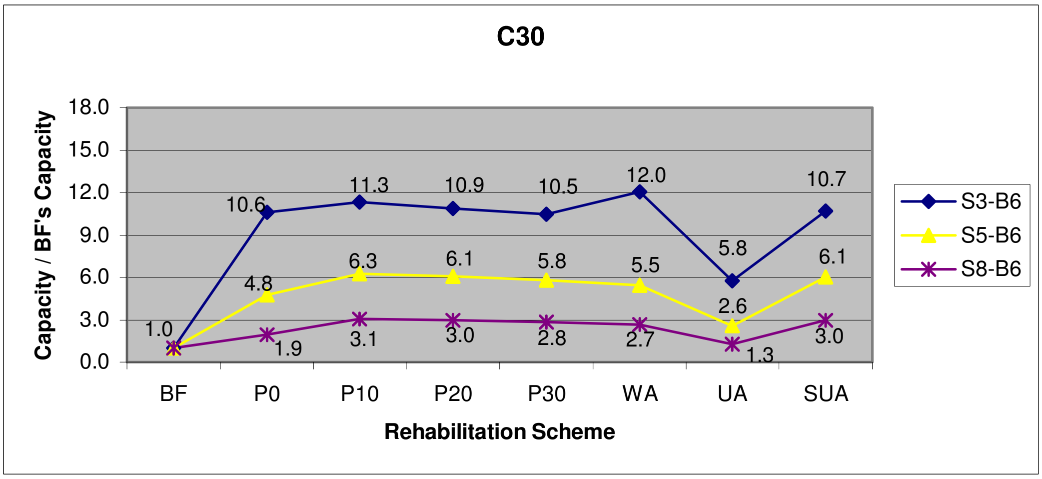


Figure 3.62: Strength increments of frames with 6m span length for C30 concrete.

3.5.3 Results of the Schemes Rehabilitated with Steel Bracing Members for frame with 2x4m span lengths

The relative capacities of rehabilitation schemes for frames with 2x4m span lengths according to Bare Frame capacity of each case separately are shown in Figure 3.63, 3.64, 3.65 and 3.66.

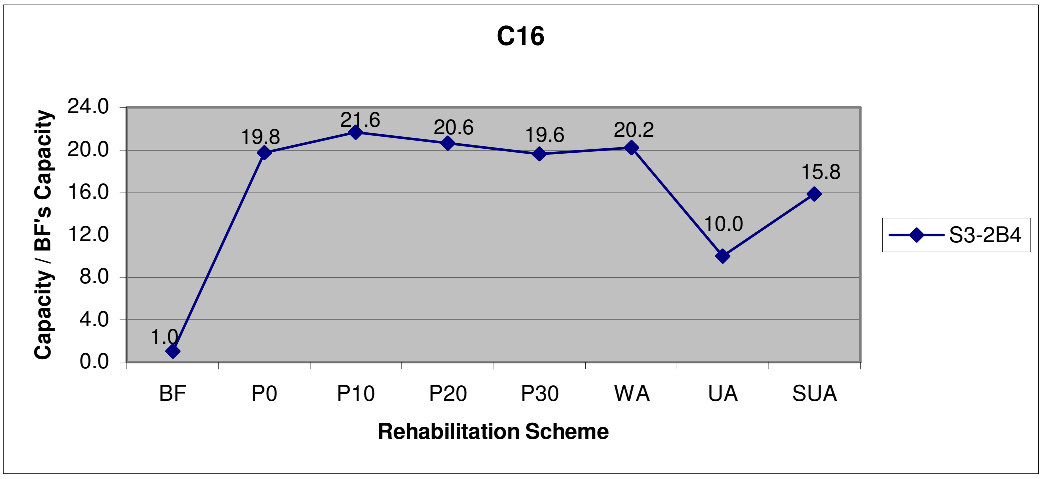


Figure 3.63: Strength increments of frames with 2x4m span lengths for C16 concrete.

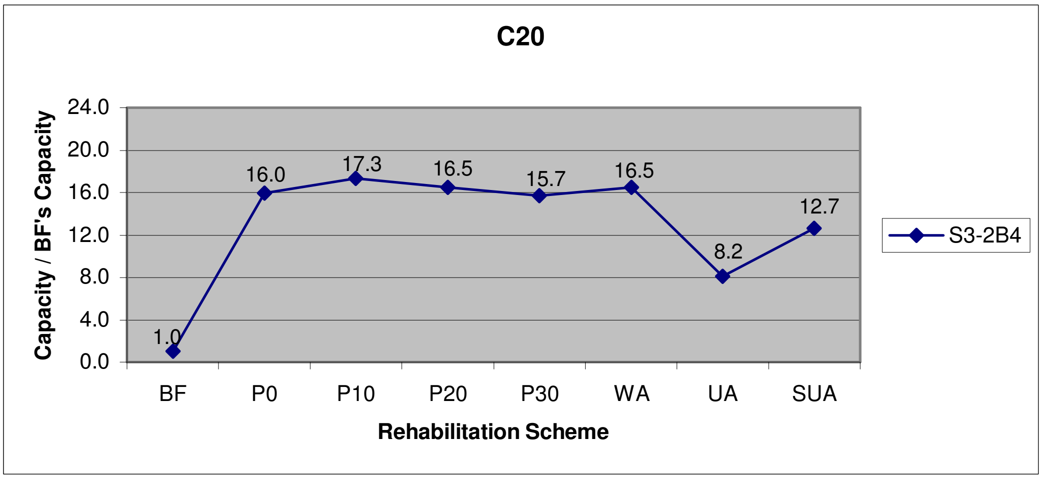


Figure 3.64: Strength increments of frames with 2x4m span lengths for C20 concrete.

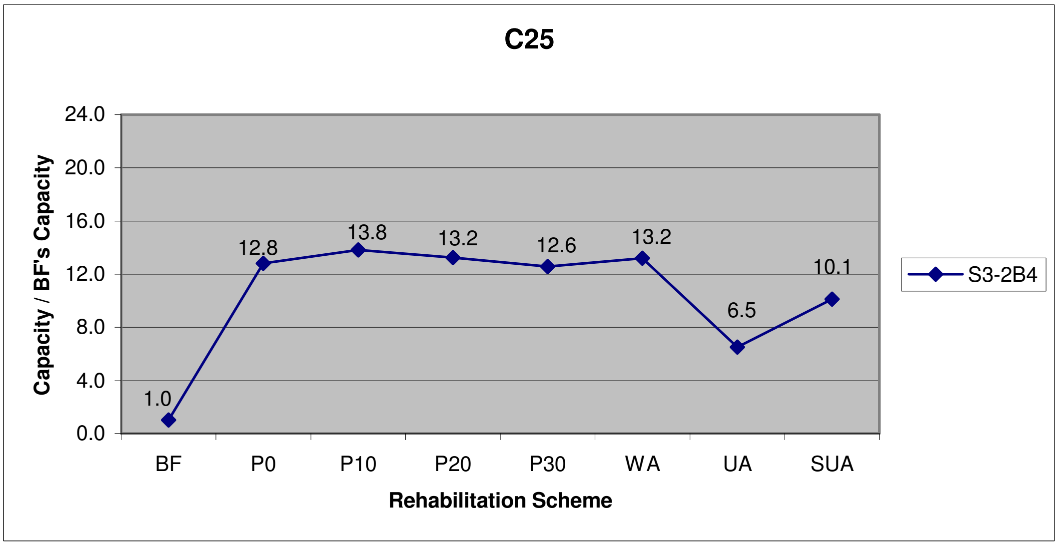


Figure 3.65: Strength increments of frames with 2x4m span lengths for C25 concrete.

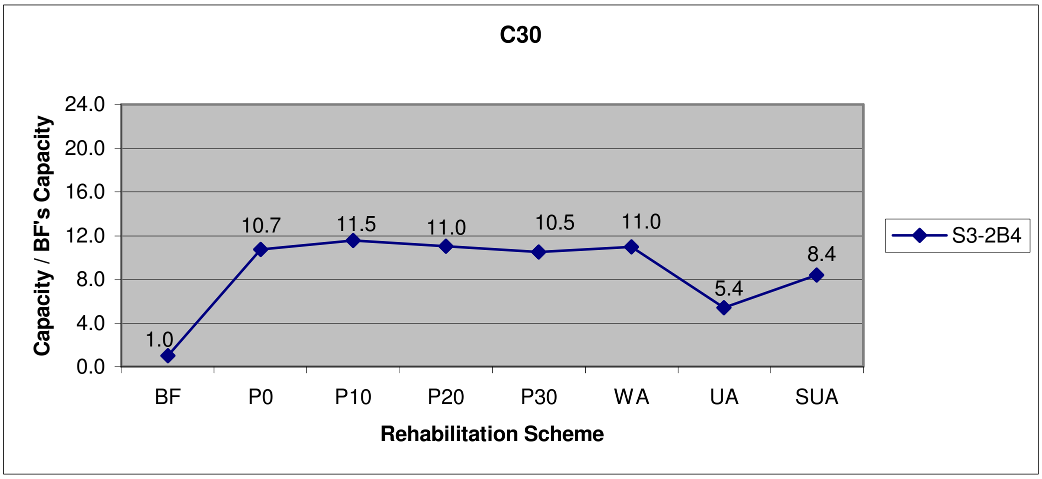


Figure 3.66: Strength increments of frames with 2x4m span lengths for C30 concrete.

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1. Summary

In this study, the use of steel bracing for strengthening of reinforced concrete frames of low, intermediate, and relatively high rise reinforced concrete frames are investigated analytically. The ultimate lateral load capacity of the strengthened frames will be determined by a load controlled push-over analysis. The post-tensioning effect of preloading is also investigated.

In chapter 1, an extensive literature survey about steel bracing system which is one of the commonly used system-level rehabilitation techniques is presented. The main advantages of the proposed procedure compared to commonly employed practice are; benefiting from the preloading of steel members and not requiring connection between steel bracing and the reinforced concrete frame at the beam-column joints of the existing frame. The preloaded steel members located adjacent to the existing reinforced concrete frame columns were used to reduce the axial compression load on the existing reinforced concrete columns. Generally, most of the existing buildings have deficiencies at the beam-column joints due to lack of transverse reinforcement and lapped splice with inadequate splice length at the joint level. These deficiencies lead to weakness of the beam-column joints. Since there is not any connection between steel members and reinforced concrete frame at these points, this rehabilitation technique does not disturb the existing reinforced concrete frame at these critical sections.

In chapter 2, the basic mathematical model of the frame structures to be analysed and design checed using SAP 2000 Integrated Software for Structural Analysis and Design software is introduced. Each model is composed of three main groups of structural components. These are the reinforced concrete bare frame, the steel frames inserted into frame bays and the steel X-bracing system in each bay which is attached to internal steel frame. A load controlled pushover analysis was conducted using an inverted triangular lateral load distribution representing seismic effect on the structure. Each model of the final structure was analyzed using the stage analysis property of SAP 2000.

In chapter 3, these model structures are analysed and design checked for the selected parameters and the ultimate lateral load capacities controlled by the existing R/C frame structures are calculated. The relative lateral load capacities of the rehabilitated structures with respect to existing Bare Frame structure capacities are calculated and displayed graphically.

4.2. Discussion of Results and Conclusions

The following conclusions are drawn based on the parametric work conducted in this study regarding the rehabilitation of existing R/C frame structures for increasing their lateral load resisting capacities for seismic effects.

- Depending on the original design and its height to width ratio, it is possible to increase the lateral load capacities of existing R/C frame structures by up to 20 times using a bracing system composed of steel X-bracing and an enclosing steel frame around it in the frame bays and without even anchoring them into the existing R/C frame structure.

- The relative effectiveness of this rehabilitation scheme decreases with the increasing frame height to its width ratio in the lateral load direction since the rate of change of axial load in the R/C columns increases with the increasing frame height for the same base shear

- It is possible to further increase the lateral load capacities of existing R/C frame structures rehabilitated by using a bracing system composed of steel X-bracing and an enclosing steel frame around it by up to 2.5 times by transferring some of the existing axial loads in the R/C columns to steel bracing system through a preloading applied to the vertical steel members of the bracing system. The positive contribution of preloading continues as long as the compression controlled failure mode of the R/C columns of the existing frame prevails. Upon a switch from compression to tension controlled failure mode, the influence of further increase in preloading becomes negative.

- It is possible to achieve the same level of capacity increase with steel X-bracing enclosed by steel end members and without anchorage to R/C frame as with the steel X-bracing without end members and whose ends are anchored to R/C frame. The bracing system is anchored to R/C frame at the joints where the reinforcement is normally very heavy. This poses a serious difficulty in real life applications. However, this observation reveals that the most difficult and troublesome aspect of the scheme can be alleviated.

- The concrete strength has a positive influence on the degree of improvement. This effect is more pronounced when the ultimate capacity of the rehabilitated R/C frame is controlled by a compression controlled failure of the R/C columns of the existing structure as opposed to tension controlled failure of the R/C columns.

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