RC 골조의 내진 보강을 위한 예압 가새의 3-D 배치

3-D Configuration Effects of Prestressing Cable Bracing Used for Retrofitting a RC Frame Subjected to Seismic Damage

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Abstract

A four-story reinforced concrete moment resisting frame damaged from an ultimate limit state earthquake is upgraded with prestressing cable bracing. The purpose of this study is to investigate the bracing configuration effects on the 3-D building response using thee different locations of the bracing systems for the retrofitted building. Since the previous work done by the author proved that static incremental loads to collapse analysis as a substitute to dynamic non-linear time history analysis was a valid alternative tool. Thus, static load to collapse analysis is solely applied to evaluate the seismic performance parameters of both the original and upgraded buildings in this study. In results, the exterior bracing system is effective in restraining torsional behavior of the structure under seismic loads, and no sudden failure occurs in this system that enhances the ductility of the building due to the gradual change of building stiffness as the lateral load increases.

요 지

본 연구는 예압 가새로써 내진 보강된 RC 골조의 보강 효과를 3차원적으로 조사함이 그 목적이다. 이를 위해, 먼저 4층 규모의 RC 골조에 극한 하중을 가한 후 예압 가새를 이용하여 보강하되 보강 위치에 따라 3 경우로 나누어 해석을 수행해보았다. 해석 방법으로써, 본 연구자가 앞서 행한 연구 결과에 의해 정적 붕괴 해석법이 비선형 동적 시간 이력 해석법의 대안책으로 훌륭히 쓰일 수 있음을 밝힌바 있기 때문에 정적 붕괴 해석만 적용하여 보강 전의 해석 및 보강 후의 영향에 대해서 평가하였다. 그 결과, 외주부에 설치한 가새가 커다란 비틀림 저항을 발휘했으며 예압 가새로 인해 골조에 균등한 강성 변화가 유도되어 급격한 파괴가 발생하지 않는 효과를 보였다.

keywords : prestressing cable bracing, earthquake engineering, seismic performance
핵심 용어 : 예압 가새, 지진 공학, 내진 성능

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1. Introduction on

The lessons learned from recent seismic events have refined the building design codes for new construction. Yet, a large number of structures currently in use were built under older codes and pose substantial risk of earthquake-caused damage. It has been revealed that the major source for loss of life and economic loss comes from poorly designed and poorly constructed existing buildings. In addition to mitigating life hazard, the fundamental goal of repairing lies in economic reason. The continuous rise in construction cost, will provide people with great incentive for upgrading old existing buildings rather than demolishing them for new construction.

Recent researches on seismic hazard abatement are two fold: the first is the assessment of building performance characteristics; and the second is to develop retrofitting approaches for deficient building.

This study deals with the second task, a retrofitting technique in which prestressing cables are used to act as bracing for a reinforced concrete moment resisting frame to enhance the seismic performance during future events. It is expected that such structures will experience inelastic deformation at certain critical location in strong or moderate seismic disturbance.

2. Objectives and scope

The first phase of work done by the author[3] has revealed that an upgrading technique using PCB(prestressing cable bracing for R-C moment resisting frame is effective in controlling the building seismic performance parameters given as strength, stiffness, and ductility. The objective of this study is to investigate the PCB configuration effects on 3-D building response by analyzing the upgraded building as a space frame using three different locations of bracing systems.

The method is only applicable to building type structures. Consequently, it is intended for upgrading the building performance parameters as pertaining to the superstructure only.

3. Assesement of original building

Seismic performance parameters of the building are evaluated performing the static incremental lateral load to collapse analysis since the reliability of the static lateral load to collapse analysis as a substitute to dynamic non-linear time history analysis has been proved from the previous work done by the author.[3]

3.1 Assesement of original building

The building is a 4-story office building, and has 7 bays with a total length of 62.9 m in the EW direction and 3 bays with a total length of 29.3 m in the NS direction as shown in Figure 1.[6] The building frame is reinforced concrete with 4.26 m story heights and its total height is 17.1 m. A typical frame from a cross section of building

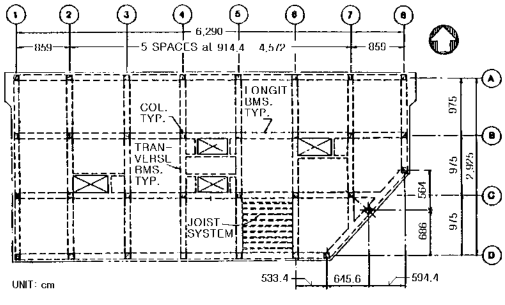

Fig. 1 Plan of office building

in the NS direction with the geometries and reinforcement of beams and columns is shown in Figure 2.

3.2 Static load to collapse analysis

Cross sectional properties as nonlinear moment-curvature (M-ø) relationships in both directions(x and y-axis) are as defined in the previous work.[3]

The torsional properties of the beams and columns are computed as shown in Table 1. [2,4]

The building is subjected to incremental static lateral load with different inclination. Consequently, the columns cross section is subjected to biaxial bending according the direction of the applied lateral load. Since the columns are square the bending moment acting about the diagonal direction must be considered, and it is determined as 549.5 kN.m, while flexural strength for bending moment about x-axis, and y-axis are computed equally as 443.4 kN.m.[5]

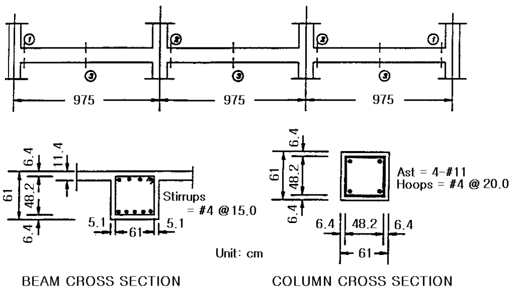

Fig. 2 Typical Beam/Column Cross Section

Table 1. Torsional Properties of the Columns

BEFORE CRACKING	AFTER CRACKING
CG: 211,924.4 kN.m^2	$C_{cr}G_{cr}$: 6,481.3kN.m^2
T_{cr}: 151.4 kN.m	T_n: 214.6 kN.m
θ_{cr1}: 7.21×10^{-6}rad/cm	θ_{cr2}: 77.56×10^{-6}rad/cm

The eccentricities for x-axis, and y-axis from the center of mass at which the incremental static force is applied, to the center of stiffness for the building are computed as 69.9 cm and 4.6 cm, respectively. Using ABAQUS®[1], the relationships between base shear and roof drift in short and long directions with various THETA (angle between the applied load and x-axis measured clockwise) are determined as shown in Figure 3 and 4. It is obvious from these figures that the building exhibited a stronger response when the lateral loads are applied at THETA=45°. The relationship between the total base shear and the total roof drift is shown in Figure 5. The figure shows that the building behavior under lateral load is mainly governed by the properties of the column cross sections.

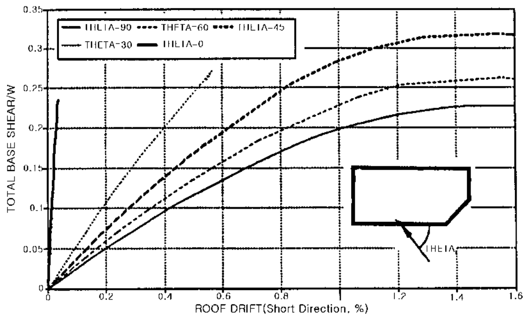

Fig. 3 Base Shear vs. Roof Drift in Short Direction

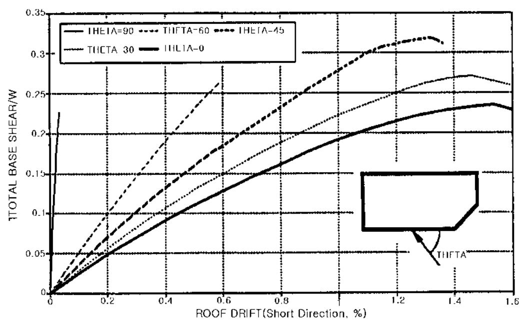

Fig. 4 Base Shear vs. Roof Drift in Long Direction

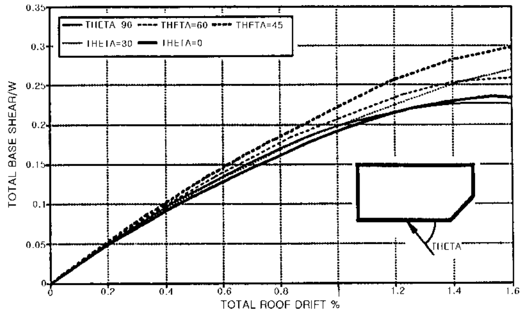

Fig. 5 Base Shear vs. Total Roof Drift

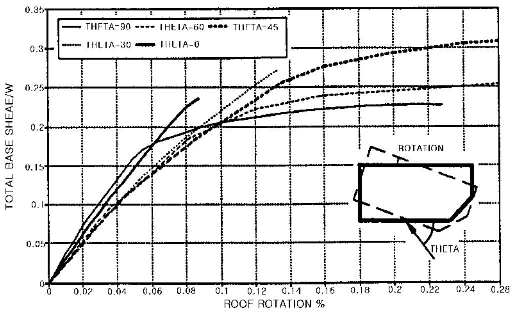

Fig. 6 Base Shear vs. Roof Rotation

The ultimate moment resisted by the column cross section depends on the applied angle of moment. Figure 6 shows the relationship between total base shear and roof rotation with various THETA. It is noted from this figure that the initial torsional stiffness when the loads are applied in short or long direction is greater than any other case of load inclination. On the other hand, the maximum torsional strength is achieved when THETA=45°.

4. A Building Retrofitted with PCB

The original building is damaged by imposing a total base shear of 0.15W, where W is the total weight of the building.[(3)] This damaged building is upgraded by applying PCB to improve its performance during future events.

4.1 Bracing Configuration

From a structural point of view, it would be desirable to brace as many bays in the building as possible so that increases in strength and stiffness are distributed uniformly. The effect of bracing configuration on the building response is studied applying three different types of configuration. It is braced in both directions since the building stiffness and strength in x-direction and y-direction are approximately equal. Fig. 7 presents the models of the three configurations.

All bracing systems are designed to resist a triangular lateral load distribution. The building is assumed to be in a highest seismicity zone. Thus, the total horizontal force is calculated for the base shear equal to 20% of the total weight of the building.[(3)]

The prestressing forces and the cross sectional areas of the cables are determined as the analysis procedure described in the previous work.[(3)]

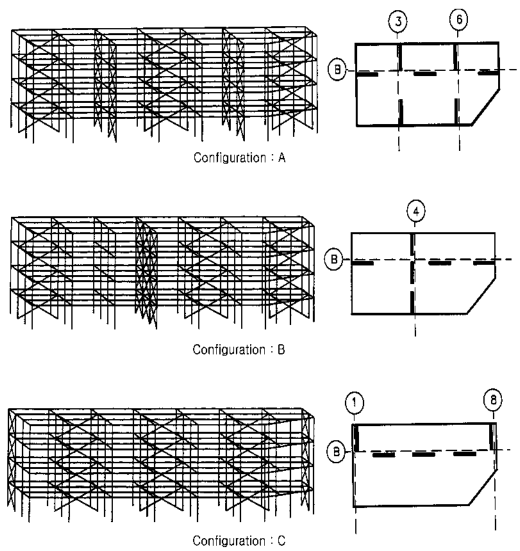

Fig. 7. Configuration of Prestressed Cable Bracing

The results are shown in Tables 2, 3, and 4. It should be noted that all bracing elements in the same story for each configuration in the short direction have the same cross sectional area and prestressing force. All configurations for the long direction, however, have the same bracing design and the results are shown in Table 5.

Table 2 Bracing Design for Configuration: A (short direction)

Story	Prestressing Force (kN)	Design Bracing Force (kN)	Cross Sectional Area (cm^2)
1st.	1,387.8	2,778.8	40.77
2nd.	1,303.3	2,624.4	39.23
3rd.	943.0	1,912.7	28.39
4th.	342.5	711.7	10.97

Table 3 Bracing Design for Configuration: B (short direction)

Story	Prestressing Force (kN)	Design Bracing Force (kN)	Cross Sectional Area (cm^2)
1st.	1,743.7	3,558.6	52.90
2nd.	1,663.6	3,291.7	49.04
3rd.	1,218.8	2,379.7	35.49
4th.	489.3	956.3	14.19

Table 4 Bracing Design for Configuration: C (short direction)

Story	Prestressing Force (kN)	Design Bracing Force (kN)	Cross Sectional Area (cm^2)
1st.	2,624.4	5,382.3	80.00
2nd.	2,580.0	5,204.4	77.42
3rd.	1,868.2	3,603.1	53.55
4th.	765.1	1,490.1	22.58

Table 5 Bracing Design for All Configurations (long direction)

Story	Prestressing Force (kN)	Design Bracing Force (kN)	Cross Sectional Area (cm^2)
1st.	1,868.2	3,781.0	56.13
2nd.	1,734.8	3,491.8	51.62
3rd.	1,201.0	2,424.3	36.13
4th.	467.06	956.4	14.19

4.2 Results of Static Load to Collapse Analysis

- Configuration A : Figure 8 presents the relationships between base shear and forces in all PCB at the first story when the loads are applied at THETA=90°. As shown in the figure the forces acting in all compression members reachers to zero at base shear equal to 0.2W. The PCBs on line ③ starts to yield at base hear equal to 0.52W, while the PCBs on line ⑥ yield at 0.58W.

It is noted from Figure 9 that the buckling of compression members occurs with a total base shear force equal to 0.2W when the load is applied in both short and long direction, and the building stiffness before buckling of compression members is constant regardless of the applied load inclination.

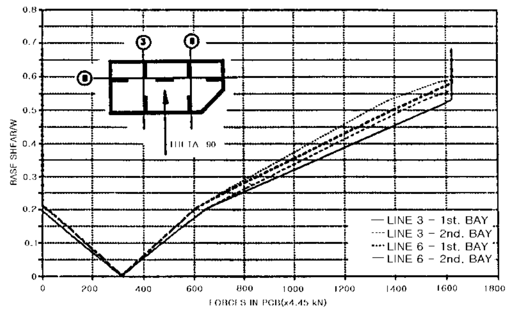

Fig. 8 Base Shear vs. Bracing Force

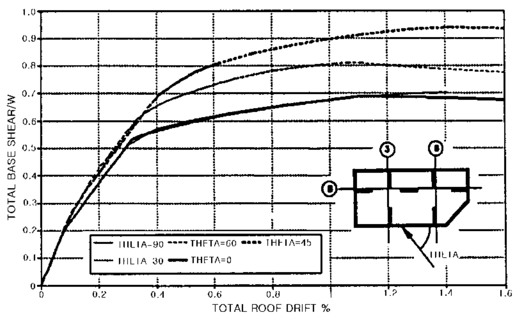

Fig. 9 Base Shear vs. Total Roof Drift

Where the bracing system is designed to resist this value of lateral load, the prestressing force is calculated such that the force in compression members ought to be equal to zero. Accordingly, as the lateral load increases these members have no effect. Therefore, the building stiffness changes at this point. After the base shear 0.2W, it is obvious that there is also a significant stiffness changes due to the effect of tension members starting to yield at total base shear equal to 0.52W when THETA=90° and 0.55W when THETA=0.

As shown in Figure 10, the building torsional stiffness is maximum when the lateral load is applied in short direction. In this case the torsional moment is resisted by the coupling between the two bracing systems on lines ③ and ⑥. On the other hand, when the lateral load is applied in long direction the torsional stiffness is minimum because there is one braced line (line Ⓑ) in this direction.

- Configuration B : It is obvious from Figure 11 that the forces in compression members decreases as the lateral load increases such that the values of these forces at base shear 0.2W must be equal to zero. After the base shear 0.2W, there is a stiffness changes due to the effect of tension members starting to yield at total base shear equal to 0.53W.

As shown from Figure 12, the building stiffness changes when the total base shear reaches up to 0.2W, at which the compression members buckle. It is noted from Figure 13 that there is no significant change in torsional stiffness with the inclination of lateral load because each direction has one braced line.

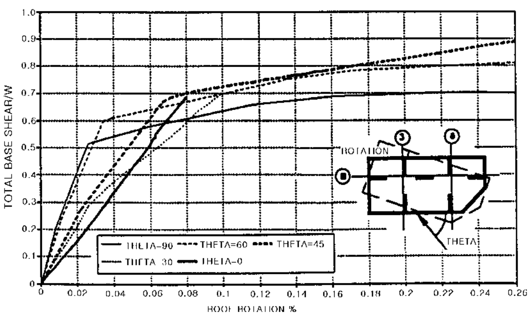

Fig. 10 Base Shear vs. Roof Rotation

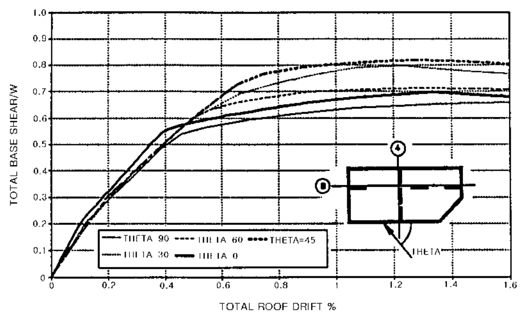

Fig. 12 Base Shear vs. Total Roof Drift

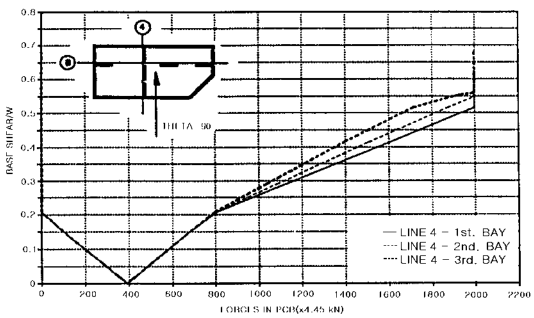

Fig. 11 Base Shear vs. Bracing Force

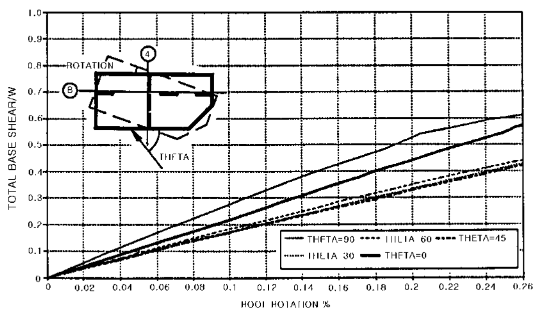

Fig. 13 Base Shear vs. Roof Rotation

- Configuration C : As shown from Figure 14, all forces in compression members are zero at base shear equal to 0.2W and the tension members of bracing system on line ① and ⑧ yield at base shear equal to 0.54W and 0.58W, respectively. It is noted from Figure 15 that the building has maximum strength when the lateral load is applied at an angle equal to 45^{o}.

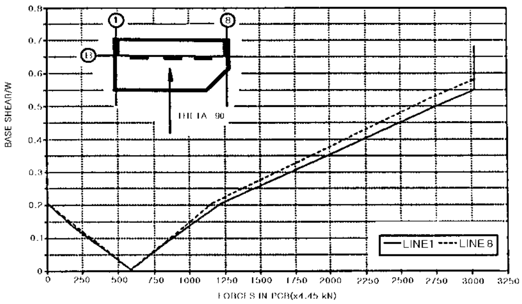

Fig. 14 Base Shear vs. Bracing Force

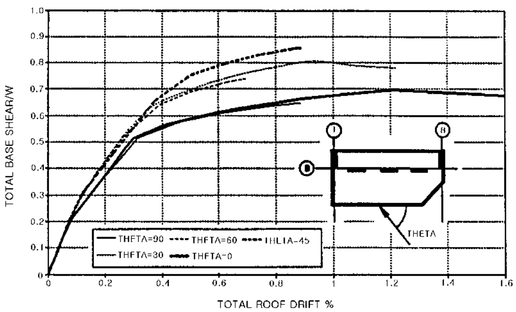

Fig. 15 Base Shear vs. Total Roof Drift

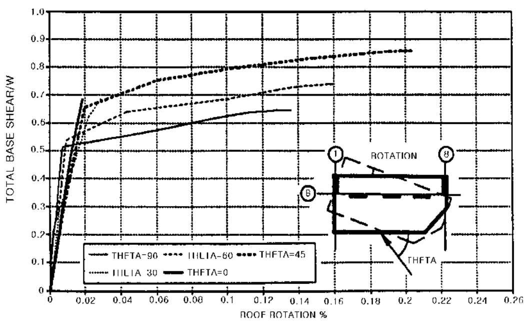

Fig. 16 Base Shear vs. Roof Rotation

Figure 16 indicates that there is no signifiant change in torsional stiffness for all cases of load inclination because the coupling between the two bracing systems on line ① and ⑧ controls the building rotation.

5. Evaluation of the Analysis Results

The first five natural periods with mode shapes of upgraded building are computed to justify to examine the validity of static load collapse analysis.(3) As shown in Figure 17, the first mode of vibration is related to the rotation about the vertical axis with a period of 0.6 sec for the configuration A. On the other hand the second and third mode of vibration are related to the displacement in short and long direction, respectively. It is obvious that the corresponding periods for both modes are approximately equal. These results agree well with static load to collapse analysis. It indicates that the upgraded building has the same stiffness in both directions. On the other hand, the fourth and fifth period are 0.27 and 0.19 sec. which are relatively small. The effect of any higher mode, therefore, can be neglected.

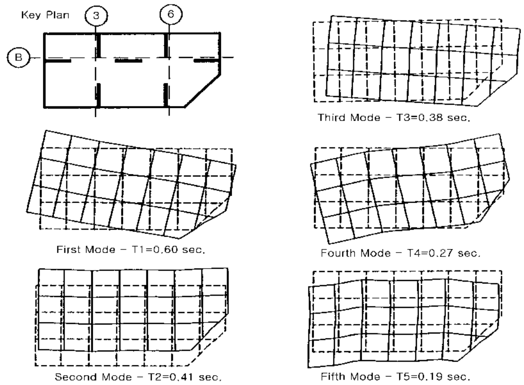

Fig. 17 Mode of Vibration-Configuration A

Figure 18 shows the first five modes of vibration for the configuration B. The fundamental period of this configuration is 1.19 sec. related to torsion about the vertical axis. The comparison between this period and the third period of original building(1.2 sec.) indicates that there is no change in the rotational stiffness by using this configuration. The fourth mode is again related to rotation, which means that the torsional stiffness of this configuration is the critical stiffness. Mode of vibration of the third configuration are presented in Figure 19.

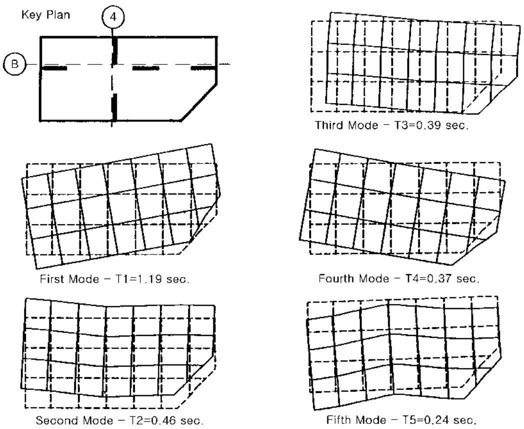

Fig. 18 Mode of Vibration-Configuration B

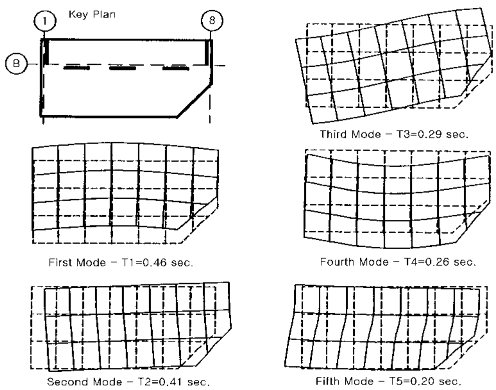

Fig. 19 Mode of Vibration-Configuration C

The first mode of vibration is related to the displacement in the short direction with a period of 0.46 sec. It is obvious that this mode combines with in-plane floor displacement. This means that the in-plane floor rigidity is not sufficient to carry the additional seismic shear to exterior braced frames. The torsional mode is the third mode and its period is 0.29 sec which is relatively small. It indicates that the increase in torsional resistance is maximized compared to the other configurations.

6. Conclusions

It is obvious that lateral resistance in both x- and y-directions must be considered regardless of the number and spacing between frames in each direction. Bracing only the perimeter frames would provide major construction advantages, but it is also advantageous with regard to torsional behavior of the structure under seismic loads. It increases in torsional resistance effectively, maintaining the structural symmetry. If only the exterior frames are strengthened slabs have to carry additional seismic shear to the exterior frames. The engineers must consider the strength and stiffness of the floor system to resist in-plane shear and bending.

The uniformity of damage distribution is thought to be a desirable goal of earthquake resistant design. The advantages of PCB technique used in this study is the comparatively small increase in mass associated with the retrofitting, and it provides quite uniform damage distribution that no sudden failure occurs, enhancing the ductility of the upgraded building due to the gradual change of building stiffness as the lateral load increases.

It must be noted that the prestressing force in the cables can significantly increase the axial load in some columns and beams. This increment in axial load must be resisted by adding additional vertical and horizontal steel elements.

The PCB technique can be an effective upgrading method to those of building structures seismically deficient or damaged. Finally, this technique should be supported by experimental work in the future.

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Notations

CG= Torsional Rigidity

$C_{cr}G_{rr}$ = Torsional Rigidity after Cracking

T_{cr}= Cracking Torque

T_n= Torsional Strength after Cracking

θ_{cr1}= Twist Angle

θ_{cr2}= Twist Angle after Cracking