**Steel Jacketing for Seismic Retrofit of RC Multi-Storey Building Structure**

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**Abstract**

Retrofitting of structural elements to enhance the building’s performance against seismic events is a matter of great importance and interest to structural engineers. Investigation on seismic retrofit based on comprehensive three-dimensional finite element modeling is not, however, quite noticeable. This paper explores the seismic retrofit of building structures based on three-dimensional finite element modeling. In this regard, a typical ten-story reinforced concrete (RC) building structure retrofitted with steel jacketing is considered for seismic upgradation. The building is assumed to have been constructed without considering the guidelines of IS 1893:2016, Part-1, and to be capable of resisting the earthquake intensities of seismic zone IV. However, the building is in demand to be capable of withstanding the seismic zone V earthquakes. Consequently, the seismic performance of the building is evaluated and reasonably retrofitted with steel jacketing to enhance its seismic performance from seismic zone IV to zone V. In view of detailed structural modeling, the shear wall and a dog-legged staircase have been incorporated in the structural modeling using a frame element with wider cross-sections. It facilitates a significantly faster computation in comparison with alternative modeling approaches, especially when considering shell elements. The nonlinear static (pushover) analysis is performed using SAP2000 software (as per the ATC-40 capacity spectrum). Pushover results verify the applicability of the applied retrofitting technique and ensure that all the structural elements of the building are below the collapse prevention structural performance level considered up to the performance point.

**Keywords:** Retrofitting, RC Columns, Pushover Analysis, Steel Jacketing, Seismic

Performance

# Introduction

Over the past two to three decades, there has been a significant increase in the collapse of reinforced concrete (RC) structures caused by earthquakes. Various structural elements may need strengthening and repair because of their deterioration over a period of time due to various reasons such as environmental conditions, not meeting the criteria of the latest version of the design code (for example, seismic provisions), aging of structure, and inadequate quality control. Priority must be given to the sustainability of the existing structure, and it has become the center of interest for many researchers in recent years. Retrofitting structural elements is the more sustainable solution as compared to demolishing the entire structure and reconstructing it again because it will help in the conservation of various resources like raw materials, time of construction, economic aspect, and overall carbon footprint of the building sector [1].RC columns are the primary load-bearing structural component, making them most likely vulnerable to deterioration [2], and they are the most important structural element in resisting seismic vibrations[3]. It is very important to assess the performance of columns and strengthen them if they do not provide adequate ductility during an earthquake to prevent the collapse of the structure. This can be achieved by restoring the seismic performance of worth-repairing columns, making the building operational without taking much time [4].

Many researchers have emphasized retrofitting RC columns by steel jacketing over the span of years and investigated different RC columns using various configurations of steel jacketing. Steel jacketing (or caging) has steel angles at the corners of the RC columns and steel straps at a few places, depending on the configuration selected along the length. This technique is not only considered practical in real life, but it is also less time-consuming and cost-effective and helps to increase the seismic behavior of the structure globally by increasing the lateral strength, ductility, and shear capacity of the structural member [5]. S. Villar-Salinas et al. [6] experimented to assess the seismic performance of a six-story RC building retrofitted with steel jacketing. The author has concluded that the proposed steel jacketing technique has improved the compressive and flexural capacity of the retrofitted columns along with the ductility of the building. F.Di Trapani et al. [7] have proposed an optimization framework for a 3D reinforced concrete building subjected to seismic loads (having 5- story 2-bays frame structure) modeled in OpenSees software, and the genetic algorithm tool in Matlab was used as an optimization technique to optimize (minimize) the seismic retrofitting cost by obtaining optimal reinforcement location and spacing between steel battens provided in columns. Nonlinear static pushover analysis was used in the N2 framework to arrive at a feasible result. The results of the study demonstrated that the proposed framework can be effectively used to minimize the retrofitting cost without compromising structural safety. A.M. Tarabia, H.F. Albakry [8] experimented with different parameters that affect the behavior of steel jacketed columns. There were ten specimens in the experiment with dimensions (150\*150\*1000)mm. Two columns were considered control columns, and the others were strengthened with steel jacketing. The author concluded that using this retrofitting technique with head connection was very efficient, and there was a significant increase in the axial load capacity of the retrofitted columns. Ezz-Eldeen [9] conducted a study to strengthen RC columns using different configurations of steel jacketing. Five rectangular RC columns were tested with different eccentricities e/t = (6.30%, 12.5%, 18.75%, 25%) served as control columns. Twelve other columns with the same dimension were divided into three groups and strengthened with two external angles (20x20x2)mm, (40x40x2)mm, (60x60x2)mm on the compression side, respectively, and two external angles (20x20x2)mm on the tension side for the all strengthened columns. Five horizontal steel plate straps (20\*2)mm were also used to strengthen all specimens. The study showed that using the steel jacketing technique was efficient, increasing the load-carrying capacity of the columns. Z.W. Shan et al. [10] conducted an experimental research with eight RC column specimens (out of which six columns were considered as strengthened columns and two columns were control columns) under a constant axial load and cyclic lateral loads and proposed a new strengthening technique that uses direct fastening steel plates. The results of the experiment validate that the proposed technique has significantly increased the lateral load capacity and ultimate drift ratio. Khair Al-Deen Isam Bsisu [11] tested 20 square reinforced concrete columns to investigate retrofitting with steel jackets technique to provide theoretical and experimental verification of the technique for concentric axial loading and concluded that retrofitting square reinforced concrete columns with full steel jackets can enhance the comprehensive strength of these columns more than twice that of the original column and it will also increase the ductility of the column. Mahmoud F. Belal et al. [12] investigated columns having cross-sectional dimensions of (200x200)mm with a height of 1200mm. The specimens were divided into two groups. The first group will act like control specimens with two columns without strengthening, and the second group will comprise five columns strengthened with different configurations of steel jackets. Based on the experimental and analytical results, the author concludes that the steel jacketing technique has increased the load-carrying capacity as well as the ductility of the column.

Many researchers have suggested that if we want a significant increase in the axial and flexural load-carrying capacity along with the ductility of an RC structure, then we must select a comprehensive retrofit technique for all the damaged frames of the structure, which will enhance the seismic performance of that structure. The external full steel jacketing technique is quite capable of retrofitting the structure effectively, and it is considered one of the appropriate techniques for retrofitting damaged RC framed structures. Based on the aforementioned literature review suggests that there has not been much-reported research on retrofitting seismically damaged multi-story structures modeled with (shear walls and staircases) retrofitted using full steel jacketing. Additionally, many researchers have investigated the performance of seismically damaged joints, or specific structural elements retrofitted using steel jacketing.

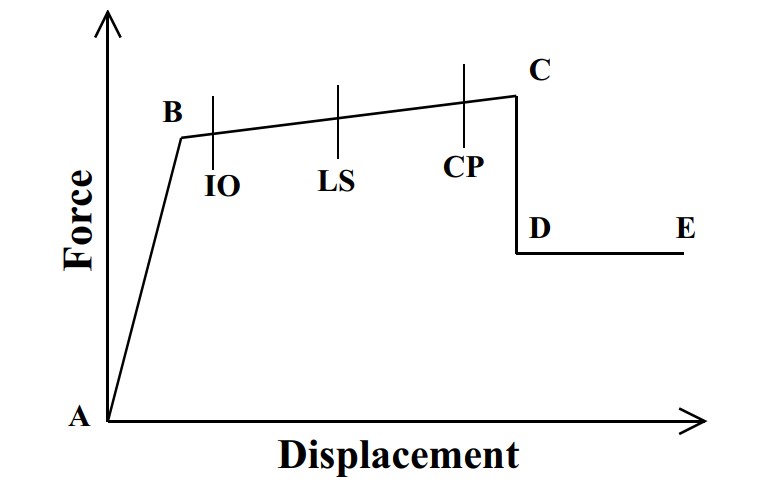
Hence, in this present study, a typical ten-story RC residential building has been considered for the purpose of investigating its seismic performance using the nonlinear static (pushover) method. To give the closest representation of the real-life structure and for better understanding, we have also incorporated the shear wall and staircase in the structure modeling using the wide beam approach, and a complete analysis has been carried out with the modeled shear wall and staircase. The selected RC structure was investigated for seismic performance if the seismic demand of the structure will go from zone IV to zone V. The structure was initially analyzed for the gravity loads, followed by assessing its seismic demands using the response spectrum method. The main objective of this study is to determine the performance level of the structure before and after retrofitting the deficient structural elements and ensure that no structural element will reach collapse prevention level after retrofitting taken up to the performance point. Pushover analysis is used to get the trend of failure step by step during an earthquake, and it will clarify the performance level of each element during a seismic event. As we increase the seismic zone factor from zone IV to zone V, some structural elements may reach the collapse prevention level before reaching the performance point as per the ATC-40 capacity spectrum in SAP2000, indicating that these elements require suitable retrofitting techniques. A full steel jacketing technique is adopted to retrofit these elements, reaching the collapse prevention level before reaching the performance point mentioned in SAP2000.

# Steel Jacketing

Steel jacketing is one of the effective and extensively used retrofitting methods to improve the seismic performance and load-carrying capacity of deficient structural elements like RC columns. Steel plates are encased over the RC columns based on the selected configuration of these plates, ensuring small gaps between the concrete and steel plates must be filled with non-shrink cement mortar or epoxy grout. These steel plates can be used in different configurations based on the desired performance levels, but the most effective configuration is the full jacketing of columns by steel plates used in this study, which is modeled using the section designer feature of SAP2000 software. This technique is suitable for retrofitting the deficient columns without enlarging the dimension, construction cost, and construction time [2]. The selected retrofitting technique is generally employed for RC columns having square or rectangle cross-sections. In this study, 10mm steel plates of Fe250 grade, providing a full jacket to the column, are used to strengthen the deficient columns, which are detected after performing a pushover analysis of the structure under gravity loads.

# Pushover Analysis

Pushover analysis is a non-linear static analysis method used to estimate the strength capacity of the structure beyond its elastic limit and up to its ultimate strength in the post-elastic range. In the process, the method also predicts potential weak area in the structure, by keeping track of the sequence of damages of each and every member in the structure using the defined properties of hinges in the structure [13].In order to perform pushover analysis in SAP2000 software there is a need to define the hinge properties for the frame elements which will indicate the sequence of damage for every element as per ASCE 41-13[14].There are two types of hinge properties available in SAP2000 for frame elements, automatic hinge properties and user defined hinge properties. In this study, we have used user defined hinge properties. For each force or moment degree of freedom, we define a force-displacement curve which will give the yield value and the plastic deformation following yield. This is done in terms of a curve with values at five points, A-B-C-D-E as shown in Fig.1.The shape of this curve is meant for pushover analysis where, Point A is origin, B signifies yielding, C represents ultimate capacity for pushover analysis, D indicates residual strength for pushover analysis and E represents total failure. The performance based design uses additional deformation measures at points IO (Immediate Occupancy), LS (Life Safety) and CP (Collapse Prevention) which are reported in the pushover analysis results of SAP2000[15].The general sequence of steps involved in performing nonlinear static pushover analysis by SAP2000 are: Modeling of the structure, Define and assign frame hinge properties, Define suitable load patterns and load cases including gravity loads and lateral loads for pushover analysis, Define nonlinear static load cases to perform pushover analysis (check displacement control and monitored displacement), Run the analysis, Review the pushover results (by plotting pushover curve, step by step showing deflected shape of all frame elements or display any other result as per requirement), Revise the model if required [15].

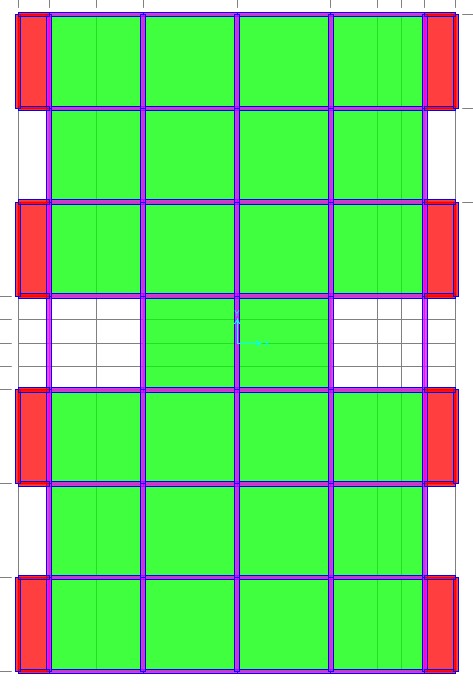
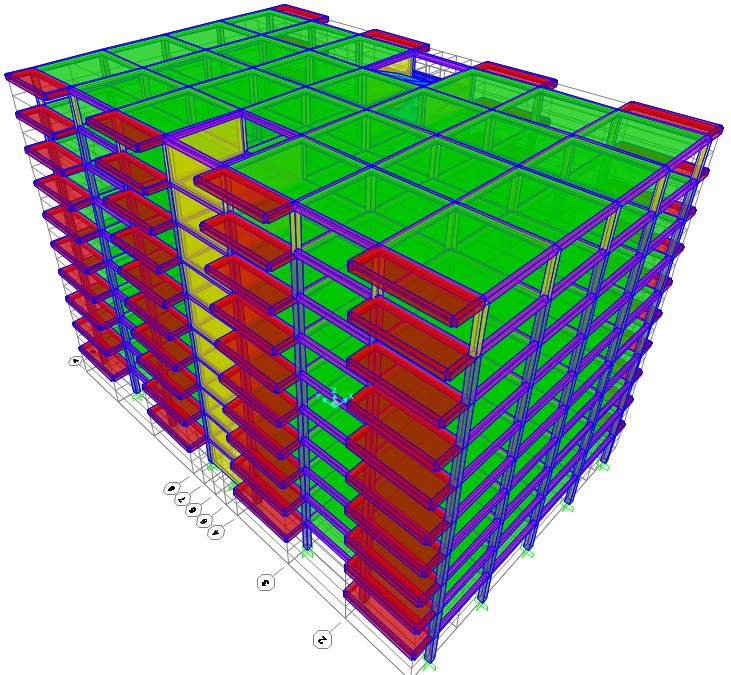


**Fig. 1**: Plastic Deformation Curve: The A-B-C-D-E curve for Force vs Displacement [14]

# Step By Step Analysis Procedure

A typical ten-story RC building was analyzed, which has been constructed by considering seismic zone IV, but as per the latest codal provision IS 1893:2016 Part-1,[16], the location of the structure comes under seismic zone V, which calls for the assessment of this building as per seismic zone V. The structure is modeled using SAP2000 software, and Fig.2a demonstrates the 3D model view, and Fig.2b shows the typical floor plan view of the building, respectively.

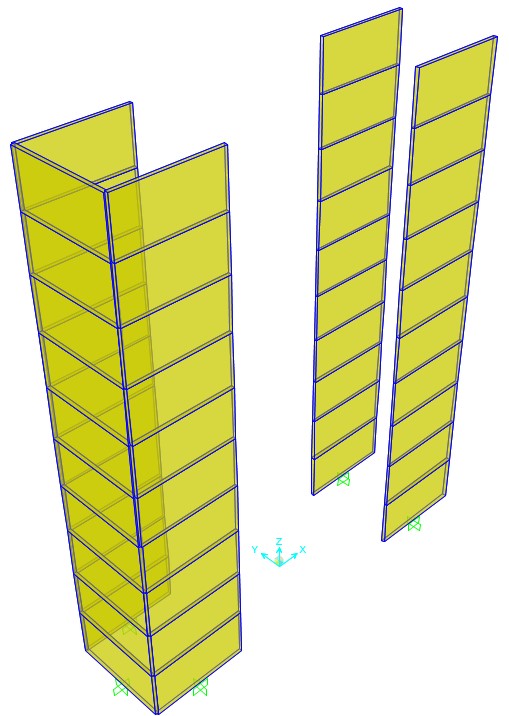
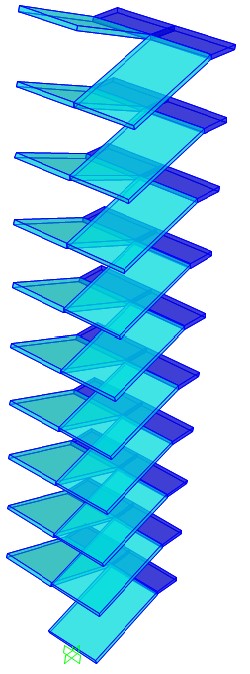
All the beams are rectangular beams with dimensions (300x400)mm, and all the columns are square columns with dimensions (450x450)mm up to nine stories, and the tenth story column dimension was reduced to (400x400)mm. The slabs used are of shell-thin type with a thickness of 150mm. The grade of the concrete used is M25 throughout. The structure is modeled with a dog-legged staircase, balcony, and shear wall to better resemble the existing structure. We have modeled the shear wall and staircase with a wide beam approach to successfully perform pushover analysis in SAP2000 without increasing the null step of



(a) (b)

**Fig. 2**: Two views of the structural model: (a) 3D view and (b) plan (top view)

nonlinear analysis. The wide beam is efficiently incorporated to substitute the shell element of slabs in the dog-legged staircase and shear wall, as shown in Fig.3a and Fig.3b, respectively. If we use a thin shell-type slab in a ten-story RC building to represent the shear wall and staircase, there may be chances that sap2000 will not be able to successfully perform the pushover analysis as it will increase the nonlinear null steps, and it may return errors without successfully performing pushover analysis.

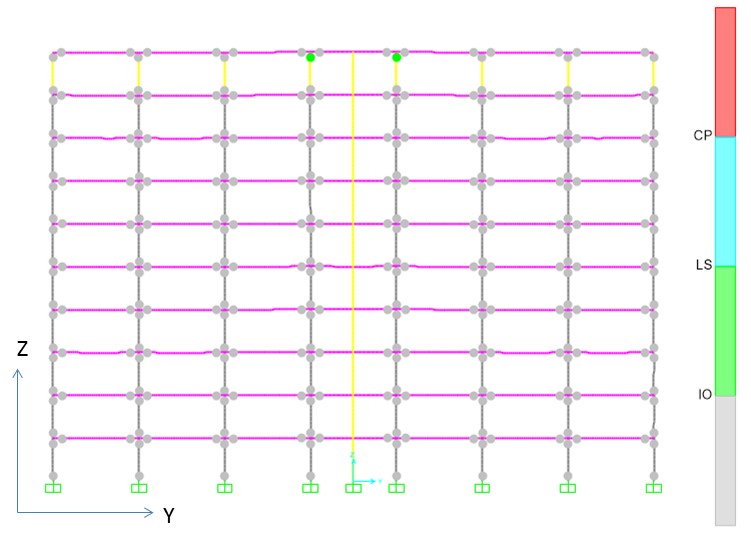
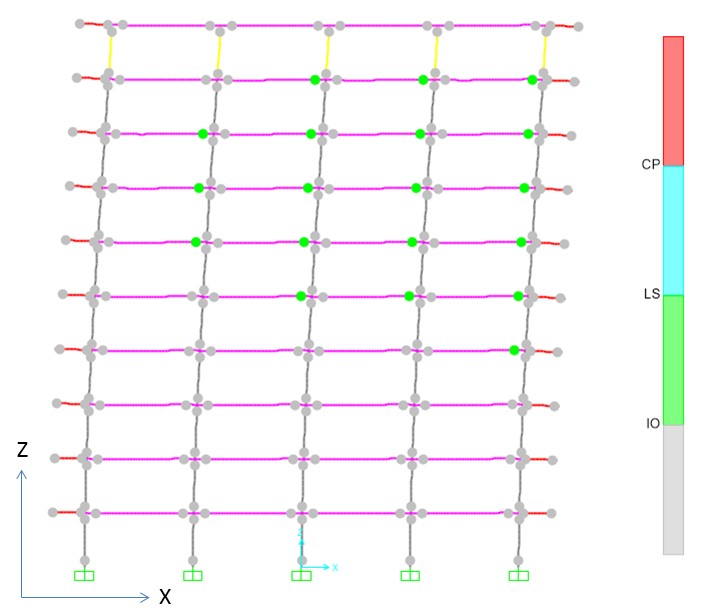


(a) (b)

**Fig. 3**: 3D view of structural elements modeled with wide beam approach: (a) Doglegged staircase and (b) Shear wall used for lift and staircase in the structural model

After the completion of the structure modeling, suitable load patterns and load cases will be created and assigned to respective frame elements and slabs as per the requirement. Here, we have used dead load (automatically assigned by SAP20000 software), a live load of 4kN/m2, and seismic load as per IS 1893:2016 Part-1[16], then we will perform nonlinear static (pushover) analysis to check the performance of all structural elements of the structure. To perform pushover analysis, we must create a nonlinear static gravity load case, followed by creating the pushover load case, which will be consistent with this gravity load case. The pushover load case includes the lateral load, which we want to apply to the structure to perform pushover analysis. Once all the load cases are created, we will define and assign the hinge properties as discussed above for all the frame elements to investigate the sequence of failure in the elements during seismic events. Once the hinge properties are assigned successfully, we will run the analysis and examine the results of the pushover load case to see the step-by-step increment in the deformed shape till the performance point given in SAP2000 as per the ATC-40 capacity spectrum [17]. The seismic zone considered here is zone V, and hard soil, which is type III, has been considered. To toggle between zone IV to zone V, we can change the coefficients Ca and Cv values mentioned in the SAP2000, and the corresponding values depending on the seismic zone and soil condition can be taken from various previously published articles [13]. In seismic zone IV, the results of pushover analysis demonstrate that all the structural elements are safe and below the collapse prevention level of performance-based design parameters considered up to the performance point as shown in Fig.4.

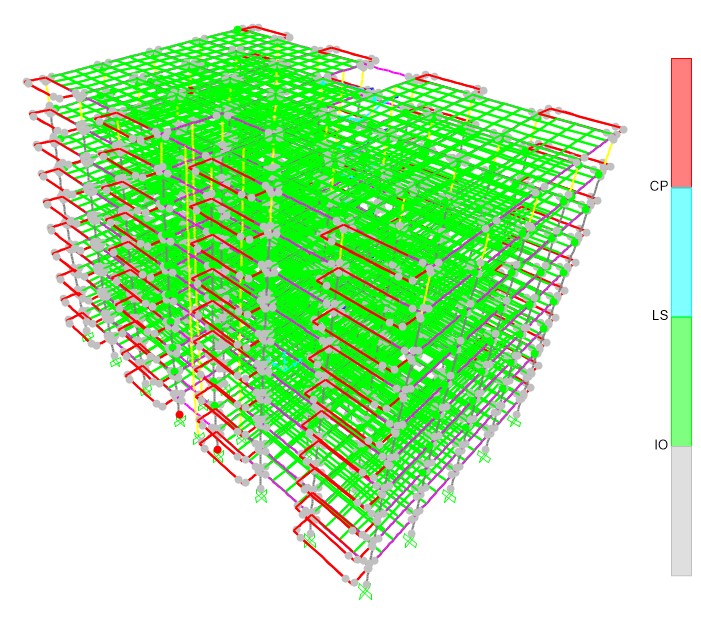
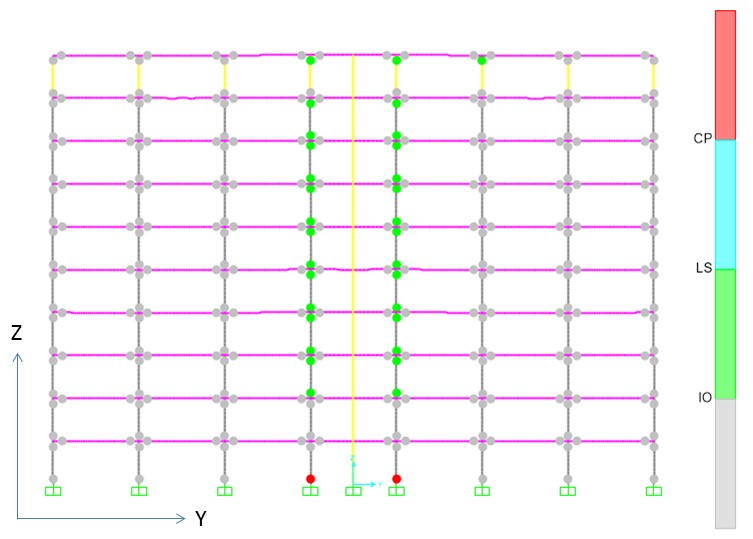
As per the recommendations of FEMA 273 (1997) [18], designing a structure up to collapse prevention assures the global stability of the structure, with the main aim being to prevent human loss during a seismic event. However, it is expected that there may be a complete economic loss of the structure as it cannot be repaired due to severe deterioration of the structure in this level of performance-based design.



(a) (b)

**Fig. 4**: Pushover deformation instances of the original building in Zone IV: (a) view of XZ plane (b) view of YZ plane

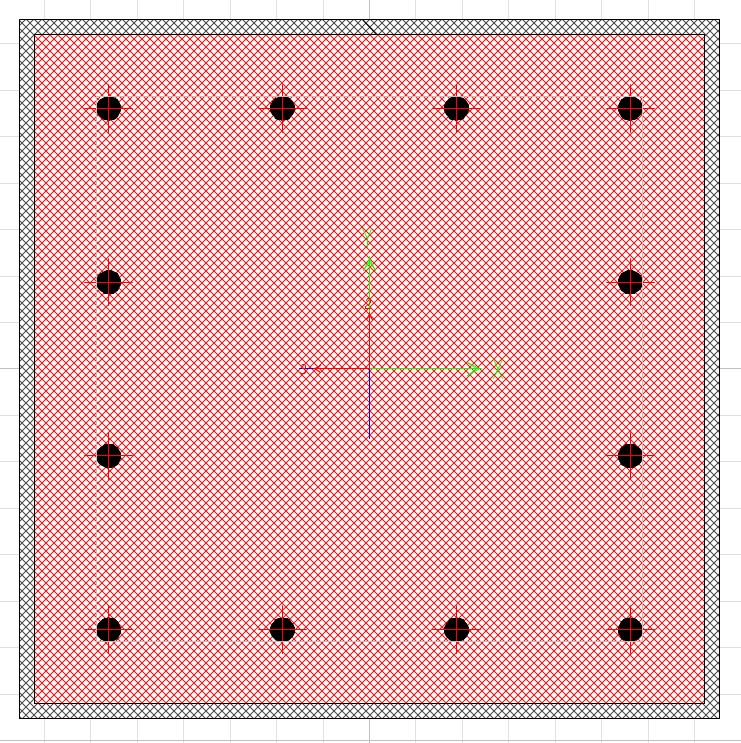
When we perform a pushover analysis of the structure for seismic zone V, the performance point will increase as per the ATC-40 capacity spectrum and the corresponding value mentioned in SAP2000. When we examine this result of pushover analysis up to the performance point, nine columns reach the collapse prevention level of the performance-based design method as shown in Fig.5 and need to be retrofitted by adopting a suitable retrofitting technique. Here, we have used a full steel jacketing configuration on all four sides using a 10mm steel plate as the retrofitting technique of the deficient columns modeled using the section designer feature of SAP2000 software as shown in Fig.6.



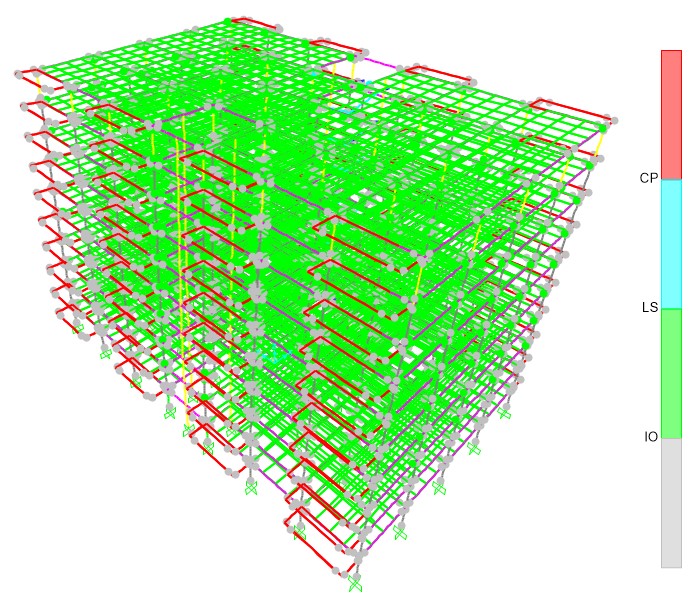
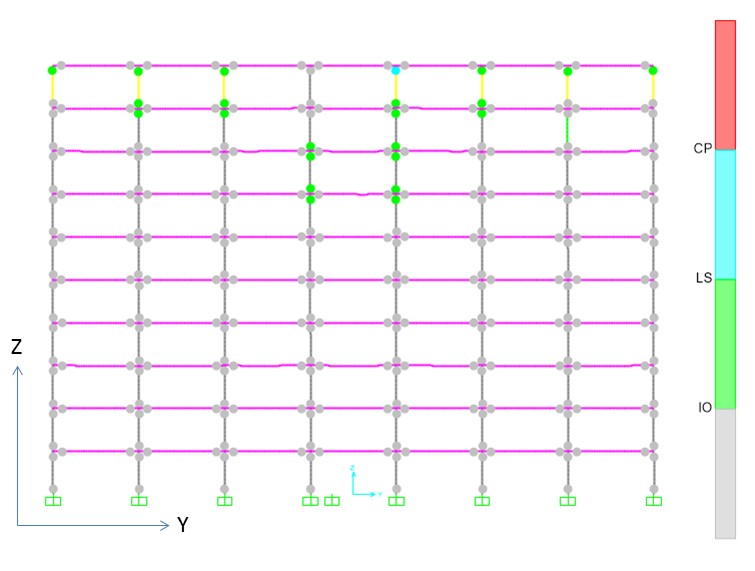
(a) (b)

**Fig. 5**: Pushover deformation instances of the original building in zone V: (a) view of YZ plane (b) 3D view of the building

Now, we will check the applicability of the applied retrofitting technique by performing pushover analysis again up to the same performance point as stated above for seismic zone V, which has nine deficient columns as shown in Fig.5. Since the deficient columns do not reach the collapse prevention level of performance-based method parameters shown in Fig.7, which verifies the efficiency of the applied retrofitting technique, i.e. steel jacketing.



**Fig. 6**: Steel jacketing detail for reinforced concrete column



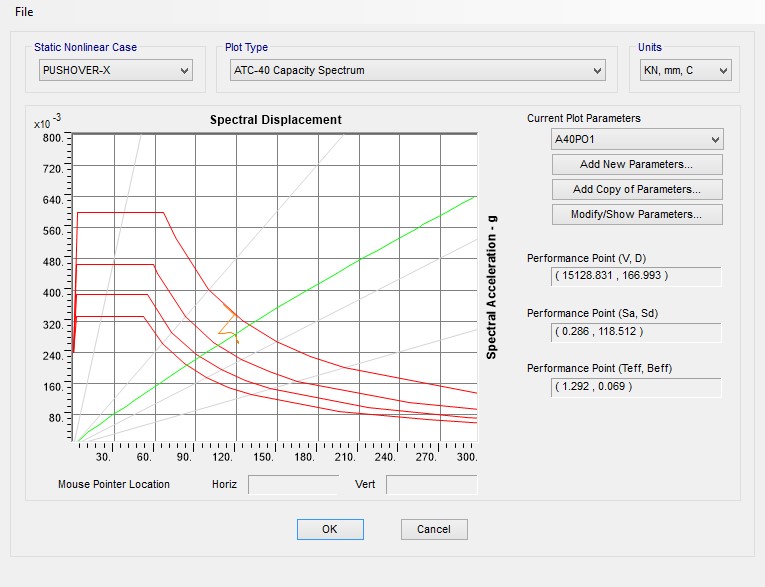
(a) (b)

**Fig. 7**: Pushover deformation instances of the retrofitted building in zone V: (a) view of YZ plane (b) 3D view of the building

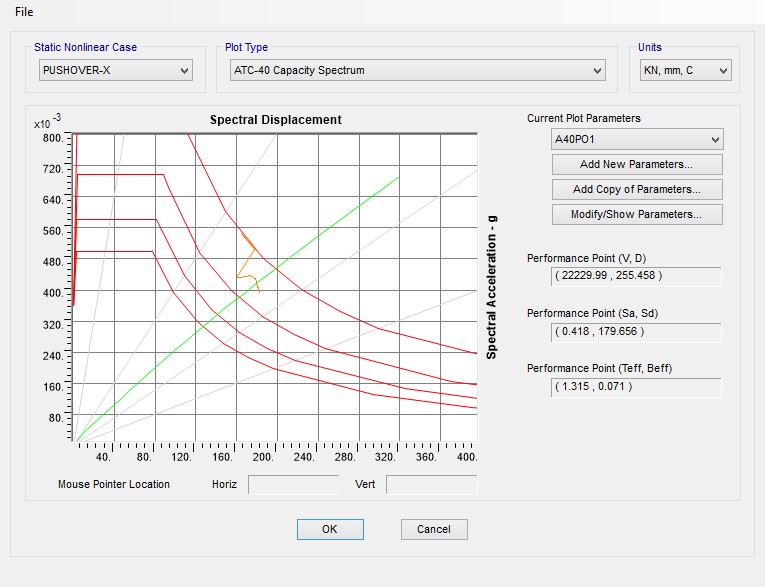
# Discussion of Results

A well-performed pushover analysis is capable of giving insight into the structural element level of performance during an earthquake. It can also provide a better understanding of the structure’s local and global inelastic deformation demands, which oscillate primarily in the fundamental mode.

The step-by-step deformed shapes of the original structure and retrofitted structure considered up to its performance point are shown in Fig.5 and Fig.7, respectively, using pushover analysis. The former figure shows deficient columns in the original structure, and the latter figure proves the applicability of the selected retrofitting technique. The performance points considered for each seismic zone were sufficiently provided by SAP2000 in accordance with the ATC-40 capacity spectrum shown in Fig.8a and Fig8b respectively.



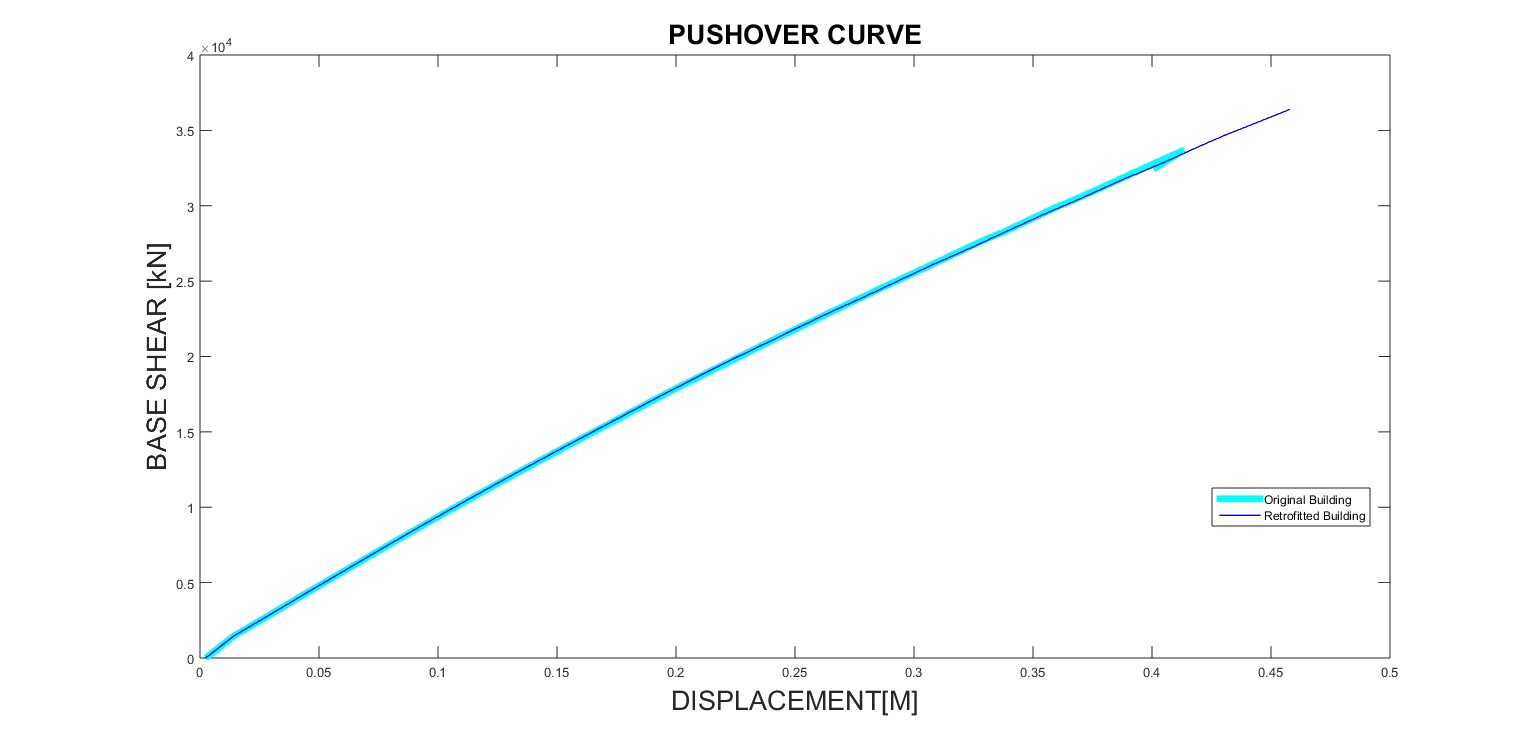
(a)



(b)

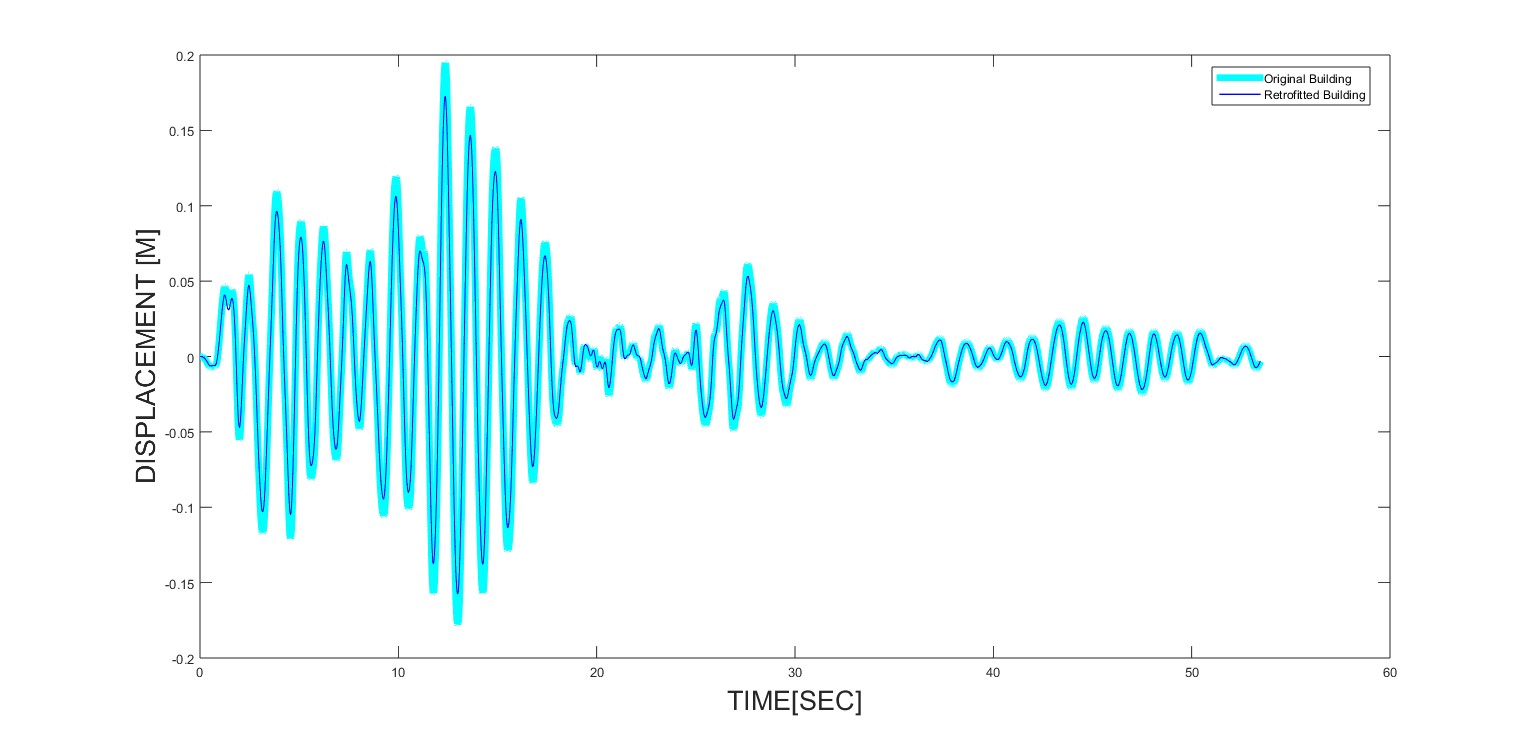
**Fig. 8**: Views of ATC-40 capacity spectrum of: (a) original Structure; (b) retrofitted structure

The pushover curve of the original structure and retrofitted structure are shown in Fig.9. If we compare these two pushover curves, it will clearly explain that after retrofitting fewer deficient RC columns using the steel jacketing technique, the base shear capacity of the structure has increased significantly, indicating better performance of the building during a seismic event.

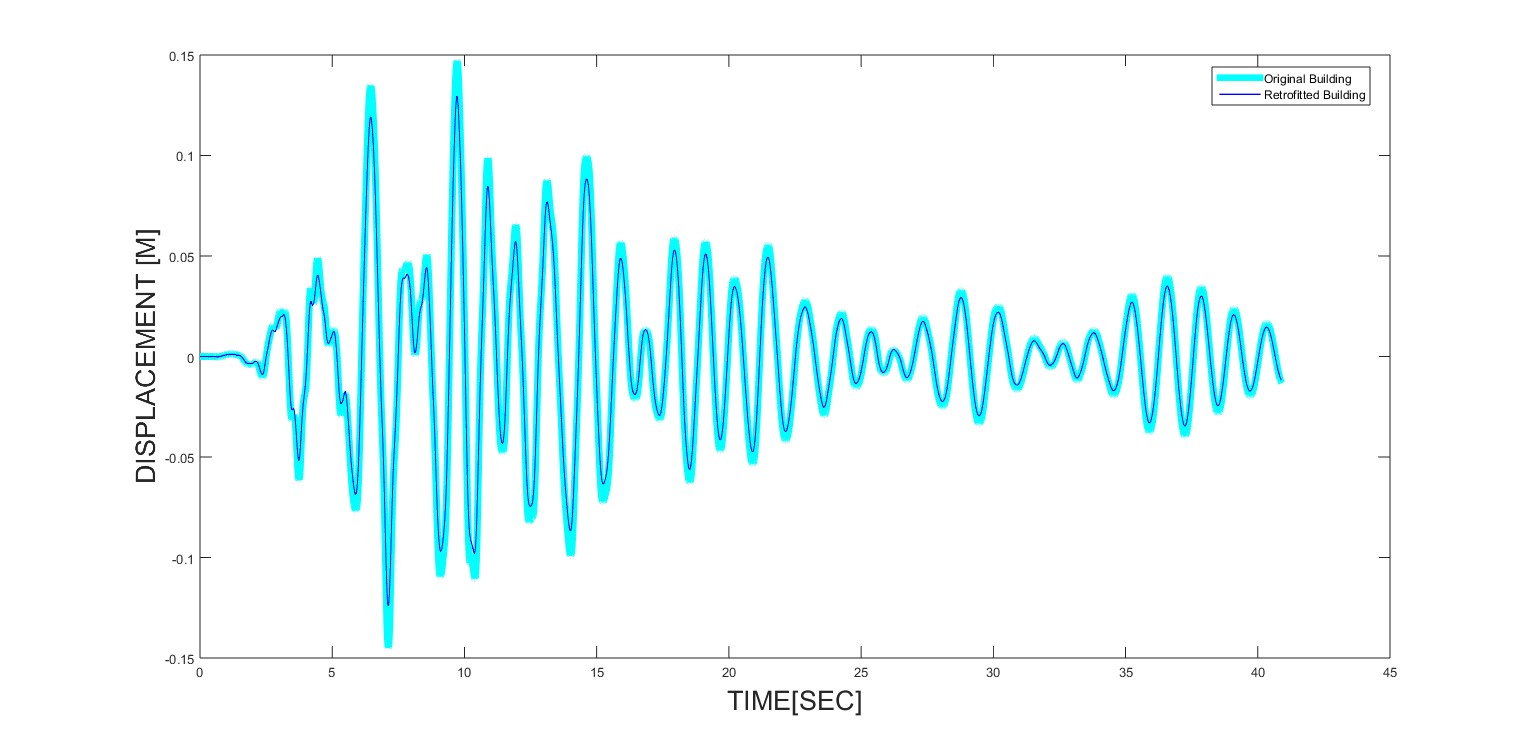


**Fig. 9**: Pushover curve of original and retrofitted building

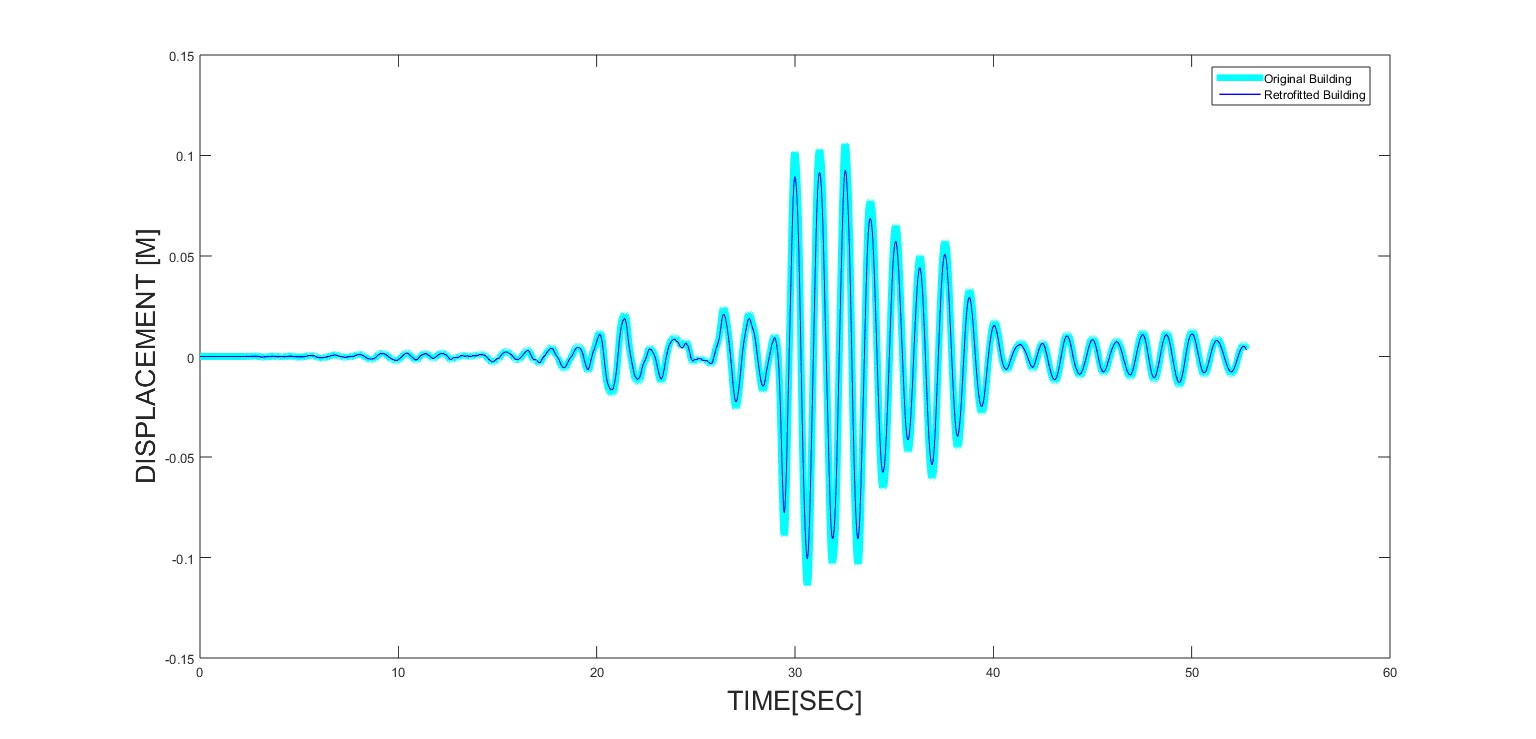
Time history analysis was also performed to assess the response of the structure under real-life dynamic forces using the peak ground acceleration of El Centro (1940), Kobe (1995), Chi-chi (1999), and Northridge (1994) earthquakes. Fig.10 demonstrates the comparison between the maximum displacement of original and retrofitted structures caused by the considered past earthquakes as mentioned above. The maximum displacement of the retrofitted building (using steel jacketing) obtained as a result of time history analysis was reduced significantly as compared to the original building, which validates the effective implementation of the retrofitting technique under dynamic force as well.



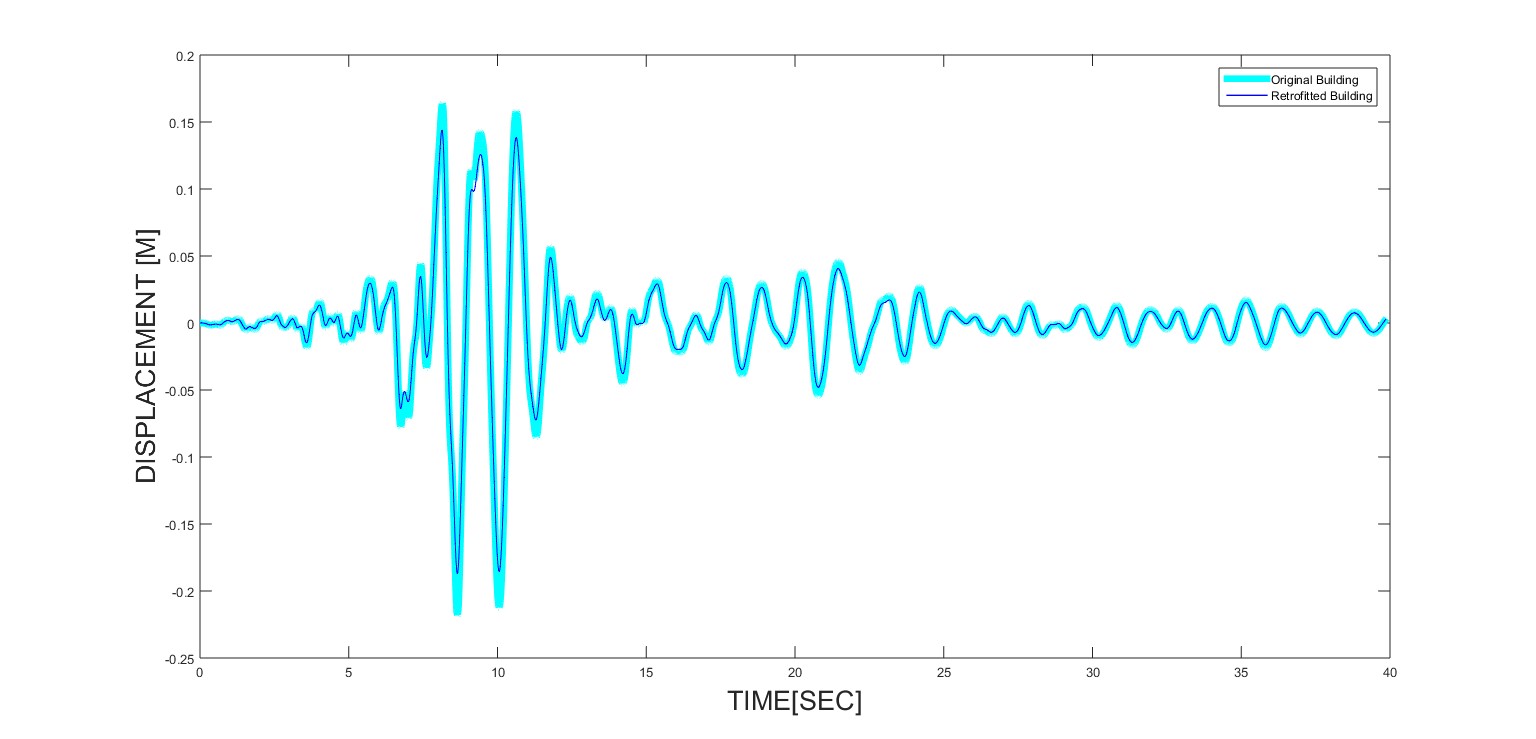
(a)



(b)



(c)



(d)

**Fig. 10**: Displacement response of peak ground motion acceleration of time history analysis: (a) el-cento earthquake (b) kobe earthquake (c) chi-chi earthquake (d) northridge earthquake

# Conclusions

The collapse of a structure is a primary concern in structural engineering. It may be addressed by strengthening the structural elements and employing appropriate retrofitting techniques to safely withstand all the applied loads during its lifespan. The present study investigated the structural performance of a structure due to seismic upgrades. The structure was analyzed, and an appropriate retrofitting technique was proposed in view of the seismic performance enhancement. Based on the analysis result of the structure, the following conclusions may be drawn:

1. The results of the nonlinear static (pushover) analysis validate the effectiveness of the retrofitting technique used to strengthen RC columns since it has increased the load-carrying capacity and overall seismic performance of the RC columns.
2. Time history analysis results demonstrate the effectiveness of the applied retrofitting technique under dynamic forces.
3. The staircase and the shear wall should be incorporated into the structure by adopting a suitable approach to better understand real-life structure performance under seismic events. The wide beam approach can be used to model the staircase and shear wall as an effective substitute for the shell element, which may return a null step error while performing pushover analysis. This approach proves to be quite successful for the modeling of the shell-type slab, and it will also facilitate the reduction of the computational time taken during the analysis by the software SAP2000.
4. The proposed retrofitting technique with full jacketing configuration proves to be a noticeable advantage, although the author encourages further investigation regarding analysis with other possible configurations in steel jacketing.

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