CHAPTER 16
CONCLUSIONS AND CONTRIBUTIONS

16.1 SUMMARY

The frequency and variation of earthquakes occurring across the globe have brought into focus the need for a comprehensive study of the behavior of the building under the forces induced due to the earthquake. With the availability of the high end hardware and software, it is now feasible to study the complex demands that are dynamic in nature. Thus, the present study was focused on a detailed parametric study to understand the complex nature of this most devastating disaster and its effect.

There are various factors which affect the earthquake and dynamic response of RC framed structures. Out of these factors, in the current study, the shape of the column was considered to be one of the factors which affect the response. A mathematical model of G+7 storey RC frame was considered for push over analysis using commercially available software SAP2000. The performance point which is the intersecting point of the seismic demand and capacity spectra was evaluated for frames having rectangular and equivalent square shaped cross sections. The study incorporated two variations in the overall plan dimensions – 6m x 6m and 6m x 9m having four panels each of 3m x 3m and 3m x 4.5m respectively for the models. The same set of models was then studied with brick infill walls modeled as shell elements and equivalent struts. Various parameters like base shear, roof displacement, number of plastic hinges, severity of hinges, effective damping, etc. were compared for the mathematical models at performance point. The G+7 RC space frame models were also studied under push over analysis with the column cross section considered as T shaped as against rectangular shaped.

Rigidity of the beam column joint is also one of the factors affecting the seismic performance of RC frames. A set of RC plane frame mathematical models with one bay one storey to two bay eight storeys was considered for study. The value of joint rigidity was varied from zero (pinned joint) to very high (fully rigid joint) with small step increment. The variation in the beam end moments was plotted against the joint rigidity for all the models. Later, RC space frame models with varying rigidity were also developed for comparing the results under lateral loads using ETABS software.

The concept of semi rigid joints having four different joint rigidities viz. 0%, 20%, 45% and 100% for all internal joints and fully rigid joints in all external frames was used to create hybrid frames. The seismic performance of semi rigid, hybrid and fully rigid space frames having square and rectangular columns for G+3 to G+7 storey RC structures with overall plan dimensions of 6m x 6m was compared using push over analysis. The concept of hybrid frames was further extended to bigger frames of overall plan dimensions of 9m x 9m, 12m x 12m and 15m x 15m.

Similar to the hybrid concept adopted for RC frames with semi rigid joints, hybrid frames with internal beams as PT beams and external beams as conventional beams was developed for comparing the seismic performance of these hybrid PT frames with frames having all RC beams and all PT beams. The G+3 to G+7 storey frames were used for study under push over analysis. Also to reinforce the confidence, the OpenSEES software platform was used to do the verification of push over analysis results obtained from ETABS software.

Moreover, the effect of introducing a floating column in a G+7 storey RC space frame having rectangular and equivalent square column cross section when a peripheral column is removed from the first to sixth storey was studied. Apart from storey drift, base shear, roof displacement, effective time period, effective damping and number and category of plastic hinges developed at performance point were also included in the detailed parametric study.

Finally, using the linear static method, the response spectrum method for Bhuj earthquake, the IS 1893 specified response spectrum analysis method, the non linear static push over analysis method and the time history analysis method as per the acceleration time history recorded for the Bhuj earthquake at Ahmedabad station, the response of the G+3 to G+7 storey frames was compared. The comparison in the response of the space frames having rectangular and equivalent square column cross sections was done using the base shear, roof displacement and drift criteria.

16.2 CONCLUSIONS

1. For a G+6 storey RC frame having an overall plan dimension of 6m x 6m and a panel size of 3m x 3m, the seismic performance of frame having rectangular shaped columns is found inferior to the same frame having equivalent square columns.
2. The results of the push over analysis for G+6 storey RC space frame indicates that the storey drift for model with rectangular columns shows a much higher storey drift at first storey level as compared to the model having equivalent square columns.
3. The number and intensity of plastic hinges developed in a G+6 storey RC space frame with rectangular columns at performance point is found much higher compared to the same model having equivalent square columns. This fact indicates a better seismic performance of the square shaped columns.
4. For an overall plan dimension of 6m x 9m for a G+6 storey building, the push over analysis indicates that the seismic performance of both rectangular and square columns is almost

similar. However, the maximum storey drift for model with square columns is less than that with rectangular columns.

5. When brick infill walls are considered in the form of struts in the push over analysis, the number of plastic hinges decreases but severity of plastic hinges developed at performance point increases for both G+6 storey models having square and rectangular columns as compared to the same without considering infill walls.
6. In case of G+6 storey RC frames, looking at the effective damping and base shear at performance point, it can be stated that square columns perform better for overall square plan (3m x 3m panel) whereas rectangular columns perform better for rectangular overall plan (3m x 4.5m panel). This is true for push over analysis with infill walls modeled as struts and even without infill walls.
7. For a G+6 storey model, T shaped columns show a better seismic performance as compared to the rectangular columns in terms of plastic hinges developed at performance point as well as storey drift which is observed. It is also clear that the rectangular column show better performance when pushed in the direction of it's strong axis and inferior performance when pushed in the direction of it's weak axis as compared to T shaped columns. This behavior is found more pronounced when infill walls are considered in the form of compression struts.
8. The seismic performance of frames with rectangular columns as compared to T- shaped columns is better in one direction and inferior in the other direction push from the point of view of roof displacement and base shear observed at performance point. This is also found true when infill walls are considered for the models.
9. It is found that the effective damping at performance point is almost the same for T and rectangular column models when infill walls are not considered but the difference is more prominent when infill walls are modeled as struts.

10. For a G+6 storey model, with an overall plan dimension of 6m x 6m, it can be concluded that equivalent T shaped columns perform better under seismic forces as compared to rectangular columns by comparing parameters like roof displacement, base shear, effective damping, plastic hinges and storey drift.
11. A study of RC plane frames from 1 bay 1 storey to 2 bay 8 storey with varying joint rigidity under lateral loads indicate that in the top storey, the beam moment shows a peak value under semi rigid conditions. This peak moment is above the moment observed if the same joints are considered as fully rigid.
12. It is observed that the peak moment occurs in the internal joint of a two bay frame at the roof level under semi rigid conditions. The ratio of this peak moment to fully rigid moment increases with increase in number of storey and reaches to a maximum of 2.89 at the inner joint of a 2 bay 8 storey frame.
13. When the plane frames up to three storeys are subjected to push over analysis considering semi rigid beam column joints, there is hardly any effect on the performance point of fully rigid frame and semi rigid frames.
14. Plane frames with semi rigid joints show a lower value of base shear and higher roof displacement at performance point when subjected to push over analysis. This indicates that frames with semi rigid joints show poor seismic performance compared to fully rigid frames. Thus, in case of pre cast concrete frames, care should be taken to ensure the joint rigidity.
15. The concept of peak moment is also observed when a space frame is modeled with semi rigid joints. The peak moment occurs only in the top storey beams under lateral loads only. This ratio increases with the increase in the number of storey. In the current study, the ratio of the peak moment to fully rigid moment is found as 2.66 for a G+8 storey space frame.

16. The effective damping at performance point increases in case of space frames with fully rigid beam column joints indicating damage in the frames with rigid joints under seismic forces.
17. It can be concluded that the concept of semi rigid joint for the internal beam column joints can be used in conjunction with fully rigid joints in the peripheral beam column joint to form what can be termed as a hybrid frame. The seismic performance of a hybrid frame for values of joint rigidity greater than 33% is quite similar to that of a fully rigid space frames. This conclusion is valid regardless of the number of storey or the column shape up to G+7 storey structures.
18. It can be concluded that for a given structure, say G+6 storey space frame, the seismic performance for a frame with square shaped column is lying between that because of the two lateral directional push for a frame with rectangular columns. This is true for G+3 to G+7 storey structures for an overall plan dimension of 6m x 6m with panel size of 3m x 3m.
19. When comparing the storey drift for G+3 to G+7 storey space frames, it is evident that hybrid frames with 0% rigidity with square columns are almost equivalent to the same frame with rectangular columns with all joints as fully rigid. This fact indicates a better performance of square columns under lateral forces.
20. The difference in the storey drift between square and rectangular columns for fully rigid joints show that the difference is minimum for G+5 storey frame and this difference increases as the number of storey increases or decreases. The maximum percent difference is found for the G+7 storey frame.
21. The storey drift is quite high for square and rectangular columns with semi rigid joints having rigidity less than 45% of that for fully rigid frames. Thus, it can be concluded that for frames having low joint rigidity, storey drift is not affected by changing the cross sectional shape of the columns. It can also be concluded that the

storey drift of hybrid frames is almost independent of column shape and the rigidity of the internal joints.

22. For a rectangular overall plan building of 6m x 9m with rectangular columns pushed in the weak direction, the joint rigidity below 45% has hardly any effect on the roof displacement for G+3 to G+7 storey frames at performance point.
23. For bigger frames with overall plan dimensions of 9m x 9m, 12m x 12m and 15m x 15m for the hybrid frame the seismic behavior changes from similar to fully rigid frame to similar to semi rigid frames at low values of rigidity. However, if one considers the rigidity of all the joints as more than 45% of that for fully rigid joints, there is very small difference in the performance between hybrid and fully rigid frames for G+3 to G+7 storey frames.
24. The difference in roof displacement at performance point between semi rigid and hybrid frames relative to a fully rigid frame decreases for semi rigid frame and increases for hybrid frame with increase in the size from 9m x 9m to 15m x 15m. This means that with increase in frame size, hybrid frames behave more like semi rigid frames. However, this difference becomes insignificant at joint rigidity of more than 45%. The same is true for base shear value at performance point for bigger frames. This trend is independent of number of storey.
25. The plastic hinges developed at performance point in all the types of frames with joint rigidity more than 45% is almost the same regardless of the number of storey for bigger size frames.
26. For G+3 to G+7 storey RC frames with post tensioned beams, it is seen that the base shear at performance point for frames with peripheral RC beams and internal PT beams is the highest as compared to those frames having all beams as RC beams and having all beams as PT beams.
27. The plastic hinges developed in G+3 to G+7 storey space frames for those with peripheral RC beams and internal PT beams are lying

in the stress level of immediate occupancy stage indicating a good seismic performance of these frames. The effective damping almost remains unchanged for G+3 to G+7 frames having a combination of PT and RC beams showing a consistent seismic performance.

28. It is observed that when floating columns are considered in a G+7 storey space frames, there is no difference in the base shear resisted at performance point when the column is omitted in the fifth and the sixth storey.
29. When the performance of frames with square columns is compared with those having rectangular columns, the parameters like effective damping and plastic hinges indicate that when a column is omitted from a particular storey rendering the column above it as floating, square columns exhibit a better seismic performance.
30. Considering the storey drift for a G+7 storey frame with floating columns, there is a local increase in the storey drift at the level where the column is omitted under push over analysis at performance point. When the column is omitted in the upper storey, there is hardly any effect of the seismic performance of the G+7 storey frame regardless of the column shape.
31. The comparison of method of analysis between the five different methods viz. linear static, non linear static (push over), response spectrum method as per IS1893, response spectrum as per Bhuj earthquake and time history analysis as per bhuj earthquake, it is clearly seen that the base shear value is highest when time history method is adopted for G+3 to G+7 storey frames. The base shear noted as per code specified response spectrum analysis is almost same as that due to push over analysis at performance point. The base shear due to linear static method is almost 10% of the base shear observed due to time history analysis.
32. When comparison is made between the seismic performances based on roof displacement or base shear of a model with square

shaped columns with that having rectangular shaped columns by any of the methods, the square shaped columns are found to be better. It is also seen that under time history loading the behavior of G+3 to G+7 storey frames do not show any pattern and hence the response is considered to be quite random.

33. When storey drift is compared by all the methods, it is found that regardless of the number of storey, the storey drift due to time history load for models with rectangular columns is quite random. Barring the case of G+6 storey frame, it is observed that square shaped columns exhibit a lower storey drift as compared to rectangular columns regardless of the method of analysis or the size of the structure for G+3 to G+7 storey frames.

16.3 CONTRIBUTIONS

1. One of the major points highlighted in the current work is the seismic performance of a low rise RC space frame under seismic and dynamic loads. The observation made throughout the current work is that by considering the shape of the column from rectangular to square, the performance of the structure can be enhanced without any change in the cost of the material. This major finding has been observed by comparing the response of the structure under various parameters. It is shown that the storey drift is less, base shear resisted is more, roof displacement is less, effective damping is less and the stress level and the number of plastic hinges are less for square shaped columns. This type of comparison is hardly found in any literature reviewed as of date.
2. One important finding of the current work is the use of T-shaped columns as against the rectangular shaped columns for improving the seismic performance. Although, a number of researchers indicated the importance of various parameters on seismic performance, a direct implication of a specific shape to be used is not found in any literature. Moreover, it may be noted that the

shape suggested is keeping in mind the preference of majority of the architects who prefer structural members to remain flush with the walls. Thus, a practical aspect is also kept in view, which satisfies architectural as well as economical aspects as the equivalent shape uses the same quantity of material.

3. The concept of hybrid frames which comprise of external rigid and internal semi rigid beam to column joints is introduced first time to show that in RC space frames, if care is taken to ensure rigidity of the beam to column joints in the external peripheral frame of a RC structure, it will behave quite well under seismic forces. This concept can be very well adopted for precast RC frames as well as in composite construction. Although a lot of work has been done on semi rigid joints in case of steel structures, one would not find much literature reporting seismic performance of semi rigid RC frames. The concept of hybrid frames which comprises of a combination of semi rigid and rigid joints is quite new for RC frames. It provides a practical solution to large number of low rise precast and composite structures used for providing housing facilities to masses by suggesting measures to improve the seismic performance considerably by concentrating on the beam column joint rigidity of peripheral frame only.
4. The present work also gives a clear guideline that in case of up to G+7 storey frames, by providing RC beams in the peripheral frame and using PT beams in the internal grids, the seismic performance can be enhanced as compared to frames having all PT beams or all RC beams for large span structures. The effectiveness of a peripheral rigid frame for resisting seismic forces without the help of a shear wall is not found in literature on post tensioned RC space frames. Thus, the concept of tube in tube which is used for very high rise structures has been effectively used in smaller sized structures in the current study which is not found in any contemporary research reviewed.

5. The work also helps in understanding the behavior of RC frames having floating columns in a regular frame. It has been pointed out that if the number of storey above the storey in which a column is omitted is less than 3, there is hardly any difference in the seismic performance of the structure. Further, it is also shown that for frames having columns omitted in a particular storey, there is a slight increase in the storey drift in that particular storey under lateral loads.
6. A comparison in the lateral forces applied to the structure due to earthquakes is shown by five different static and dynamic methods. This enables the reader to understand the difference in the forces which are applicable to a given structure. Hence, a user can decide on the method to be used for lateral load analysis based on the importance of a structure.
7. The detailed parametric study carried out in the present work may serve as a guide line for structural engineers who can decide on the method of analysis to be adopted or the shape of the column to be adopted or the rigidity of the joint which can be specified considering the ease of construction, importance of the project and various other aspects. Thus, the current work can act as a means of optimizing the use of material and a step towards constructing robust structures which can save life and property against one of the most unpredictable force of nature – the earthquake.

16.4 FUTURE SCOPE

1. The current study was limited to low rise structures up to G+7 storey only. The same work can be extended to cover space frames up to 12 stories.
2. The irregularity of the structural frame work can be taken up to study the effect of seismic forces on the same.
3. The other column shapes like plus shape and rectangular columns oriented in random directions can be considered to carry out the

analysis under lateral loads and to compare their seismic performance.

4. The effect of shear walls in the frames can be considered for analysis as structures beyond four storey are bound to have a RCC lift shaft.
5. Seismic analysis can be carried out by considering a high performing material like ECC in the beam column joint of the frames.
6. RC frames having soft storey can be studied under push over analysis and a general solution for improving their seismic performance can be worked out based on the findings.
7. A large number of RC framed structures are existing in our country which are designed for gravity loads only. Thus, a study can be taken up which designs a typical RC framed structure for gravity loads only and then subject it to push over analysis. A parameter may be identified which is causing the highest damage under seismic forces. Some general solution can be worked out as a retrofitting measure to enhance the seismic performance of such deficient frames.
8. Seismic performance may be compared for RC frames with various cross sectional shapes like T, L, +, etc. apart from the rectangular and square shapes for low rise RC frames. The best shape may be selected for better seismic performance using the well known optimization technique such as Genetic Algorithm. However, it may require proper fusion of hard and soft computing tools and a tremendous of computational effort.
9. Economics is one of the major driving force in deciding the method and material of construction, especially in case of low rise apartment type housing units. Working out of the cost difference in designing a building to a desired performance level of life safety and immediate occupancy using push over analysis will be certainly an useful extension of the present study.
10. Investigations can be carried out for RC frames having walls with light weight concrete blocks (Autoclaved Airated Concrete) instead

of the conventional bricks. Study of seismic performance from the point of view of reduction in seismic weight and increase in the strength of equivalent strut used for infill may prove fruitful.

11. The effect on push over analysis results obtained by introducing elastic springs at the foundation level instead of considering them as fixed is one important parameter which can be studied. The study can be carried out for three broad categories of soils, viz. soft, medium and hard.
12. A cost effective technique, say introducing a sand bed, may be developed to modify the foundation level details so that the foundation can act as a partially base isolated structure reducing the effects of seismic forces on the buildings.
13. A more time consuming and elaborate method of seismic analysis is the non linear time history analysis. This may be carried out to the set of RC frames defined in the current study to highlight the difference in seismic performance.
14. Connections for shear, bending moment, thrust, and torque may all posses a certain amount of flexibility but the most important of these is the rotational type that transmits bending moment. This type of connection was discussed in detail in the present work in conjunction with the plane and space frames. The idea may, of course, be extended to other types of connections and other types of framed structures.
15. Virtual reality aspects may be incorporated to visualize changes in the behavior of a building under different parameters in case of earthquake. However, it may require scripting of output of SAP into 3DS Max software and high performance computing.
16. Complex behavior of mode shapes of higher order for a dynamic load on the building and such other complex principles can be very well demonstrated in class rooms by developing virtual reality platform. Thus, educational applications may be explored in depth.