CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 General conclusions

This thesis presents the results of the study on seismic retrofitting of substandard beam-column joint by the proposed Planar Joint Expansion Method. The method is based on a two-dimensional expansion of joint using cast in-situ concrete, dowel bars and steel brackets. The study is divided into 4 parts. The first part is the development of a simple seismic evaluation procedure and the results of seismic performance of existing buildings in Bangkok. The second part is the experimental work for seismic retrofitting of sub-standard beam-column joint by planar joint expansion method. The third part is the nonlinear finite element analysis and the last part if the development of strut-and-tie model to analyze the strengthened beam-column joint. The objectives of this thesis are to study seismic behaviors, performances and parameters affecting planar joint expansion in upgrading substandard beam-column joints. From experimental results and analytical modeling, the following conclusions can be drawn.

1. A simple seismic evaluation method for reinforced concrete building constructed as beam-column rigid frame has been developed. The proposed method is simple to use and suitable for practical designer. The method consists of DCR determination, reinforcement detailing check and failure mode investigation.

2. The DCR determination is intended to check the safety of building under code-specified lateral load. In the method, the linear static analysis of building structure is required. The reinforcement detailing check is meant to check the toughness compliance with the seismic design codes.

3. The investigation of failure mode consists of two flowcharts, namely, load flowchart and yielding flowchart. The input data to the flowchart are DCR and structural indices. The load flowchart is to check the failure of building under code-specified earthquake load. The yielding flowchart is to check the failure of building after some members yield. The use of these flowcharts enables the determination of staged failure sequence.

4. When applying this assessment procedure to 15 existing reinforced concrete beam-column rigid frame buildings designed and constructed without considering seismic effect in Bangkok which cover schools, apartments and governmental offices, the results reveal vulnerability of these medium-rise buildings. It found that no buildings satisfy the reinforcement detailing requirement, because of the lack of sufficient transverse reinforcement in beam, column and beam-column joint and non-seismic detail of hook anchorage. Based on DCR, 10 out of 15 buildings show some failures in the members under code-specified earthquake load. The failure mode investigation shows 42% beam flexural failure, 38% joint shear failure and 20% beam shear failure. The load flowchart failure check is less critical than yielding flowchart because of traditional working stress design approach for RC structures in Thailand with lower allowable compressive strength of concrete and steel compared to ultimate

strength design codes. Another reason is the presence of lift core that reduces the forces transmitted to beam-column frame.

5. According to the investigation, the joint shear failure is identified to be one of the most critical failures in RC buildings. The failure in the joint may lead to the entire collapse of the building.

6. The "Planar joint expansion" is proposed as a joint retrofitting method in this thesis. The method is based on enlarging the joint in two dimensions by cast in-situ concrete, dowel bars and steel brackets. The method is comparatively easy in application and cost-effective since conventional materials are used. The method is also architecturally desirable because the planar expansion can be hidden in partitions.

7. Experimental results verify that planar joint expansion is a promising technique to upgrade stiffness, strength, energy dissipation and ductility of substandard beam-column joint. The planar joint expansion can change the failure mode from brittle joint shear to flexural failure in beam. The location of plastic hinge is moved from column face to the edge of expansion. Horizontal joint shear stress and anchorage bond stress of beam bars are significantly reduced in retrofitted specimens due to the increase in joint area and column depth to bar diameter ratio.

8. The triangular and rectangular joint expansion produces similar result. The rectangular expansion is more effective to delay spalling of concrete at compression zone in beam and buckling of longitudinal beam bars. The post-fabricated joint expansion performs equally well compared with conventional construction in which the joint expansion is cast together with beam and column. Hence, the method is applicable to both new constructions and retrofitting works. The construction joints between specimens and joint expansion do not render poor cyclic behavior in retrofitted specimen. The thickened parts are also beneficial to suppress buckling and fracture of beam bars and prevent spalling of concrete cover. The steel bracket joint expansion performs equally well compared with cast in-situ concrete. A better performance is obtained if that element has high ductility.

9. The specimen retrofitted only with planar joint expansion in upper corner is successful to prevent joint shear failure, while specimen retrofitted only with lower corner cannot. This may be related to the amount of top and bottom bars.

10. Too large planar joint expansion may produce undesirable shear failure in beam and column due to shortened member length. But too small planar joint expansion may not be adequate to reduce shear transmitted in the joint. The selection of the expansion size must therefore be done with care, considering all aspects ranging from technical to construction feasibility.

11. The formation of diagonal cracks along the edge of expansion indicates the existence of compression struts formed in the opposite pair of expansion. The alternate tensile and compressive strains measured in the dowel bars of the expansions also indicate the alternative struts and ties around the edge of the expansion.

12. The shear stress transmitted in the joint panel is not the same as that transmitted in the beam sections within the joint expansion. Shear stress transmitted in

the beam sections within the joint expansion is generally lower than that in the joint panel. Thus, the increase in joint shear capacity is not in proportion with the increase in effective joint area. Consequently, the ACI design method based on horizontal joint shear concept may not be readily applicable for strengthening design using planar joint expansion.

13. The nonlinear finite element based on smeared crack approach is shown to capture the salient behaviors of beam-column joints strengthened by joint expansion. FEM analysis shows close agreement with experimental result. The FEM analysis can satisfactorily reproduce the load-displacement envelope as well as hysteretic loops of the tested specimens. The linear finite element analysis reveals strut mechanisms in joint panel, beam sections within the joint expansion and planar expansion.

14. The strut-and-tie model is developed with the aid of nonlinear finite element analysis and experimental result to serve as a rational mechanical model to analyze the strengthened specimens. Strut-and-tie model can capture the salient characteristics of beam-column joint strengthened by planar expansion. The strut-and-tie model compares well with experimental result in terms of column shear force, measured strain and failure mode.

15. Strut-and-tie model can also capture the nonuniform shear stress distribution in the joint panel and in the beam sections with the expansion. It can predict the reduced tension in longitudinal steel at column faces and the decrease in horizontal shear force transmitted in the joint panel. The effect of the expansion size can be qualitatively predicted. The reduction in horizontal joint shear force is caused by the reduction in the longitudinal compression struts in beam and column at the joint faces as a result of the resistance provided by the inclined strut formed in the expansion. All these capabilities show that strut-and-tie model can serve as a rational design tool for practicing engineer.

16. The strut-and-tie model is also capable of predicting the exterior beam-column joint strengthened by planar expansion. The comparison with nonlinear finite element analysis confirms that the proposed strut-and-tie model can serve as an analytical tool to analyze the exterior beam-column joint too.

8.2 Recommendations

The research works conducted in this thesis is not perfect and there are still limitations as one single method cannot retrofit all kinds of structures. There are still a lot more works that need to be done towards the goal of increasing the seismic safety of the buildings. The followings are given as recommendations for future work.

1. Although the joint expansion method is promising to prevent joint shear failure and to encourage plastic hinge in beam, it has limitations. The method may cause increased shear in beam and column due to shortened member length. Thus, the maximum size of expansion is very important to prevent joint shear failure mode and the consideration must be applied to prevent member shear failure. Too large planar joint expansion may produce unintentional member shear failure but too small planar joint expansion may not be adequate to reduce shear transmitted in the joint.

2. A larger number of buildings should be collected and studied. The scope of work should extend to high rise buildings and other infrastructures.

3. The nonlinear dynamic analysis of RC buildings strengthened by planar joint expansion should be conducted to the entire building to investigate the entire structural response in the structural level.

4. The planar expansion using steel bracket should be studied in more details. The feasibility of using other materials such as ferrocement, cold-form sectioned should also receive critical studies.

5. The experimental study should also extend to exterior beam column joint and joint with other configurations such as joints with beams on four sides or with the attached slabs. The effect of upper and lower planar expansion should also receive further study to determine its influence with regards to the ratio of bottom and top reinforcements in beams.

6. The strut-and-tie model should be enhanced to take into nonlinear cyclic effect in order to capture the cyclic performance of the method.

7. More parametric studies using nonlinear finite element analysis and nonlinear strut-and-tie model should be carried out to propose a simple strengthening design method that will be easy for use by practicing engineers.