Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

12-3-5

EVALUATION OF TECHNIQUES TO REPAIR MODERATE EARTHQUAKE DAMAGE

Catherine E. FRENCH[1], WenJen TSAI[2] and Greg THORP[3]

[1]Department of Civil Engineering, University of Minnesota, Minneapolis, Minnesota, U.S.A.
[2]Student, Polytechnic University, Brooklyn, New York, U.S.A.
[3]Design Engineer, Brown-Mpls. Tank, Eagan, Minnesota, U.S.A.

SUMMARY

The effectiveness of two methods used to repair moderately damaged reinforced concrete structures with epoxy were investigated. A vacuum impregnation technique was used in the VI test series; pressure injection was used in the PI test series. The effects of restoring bond between the concrete and the reinforcement in the joint were of particular interest. Both techniques worked quite well in restoring the strength, stiffness, energy dissipation capacity and bond.

INTRODUCTION

Epoxy pressure injection has often been used to repair small cracks (<0.25 in. (6 mm)) in structures suffering moderate earthquake damage. Results of previous research (Refs. 1-4) have indicated that structures repaired by epoxy pressure injection behave quite satisfactorily except in restoring bond between the reinforcement and the concrete (Ref. 1).

Vacuum impregnation is another method of introducing epoxy into damaged concrete. This method has been used in Great Britain to repair and preserve a wide range of deteriorated structures including bridge piers, sculptures, delaminated parking ramps and pavements.

An investigation was conducted at the University of Minnesota to evaluate the effectiveness of the two techniques particularly with respect to the restoration of bond between reinforcement and concrete. Two reinforced concrete interior beam-column subassemblages were subjected to identical cyclic lateral load histories to produce simulated earthquake damage. The damaged specimens were then repaired by one of the two repair techniques. After a period of approximately four weeks, the specimens were again subjected to the same cyclic lateral load history. The measured response histories of the original and repaired structures were subsequently compared and evaluated.

DESCRIPTION OF THE TEST SPECIMENS

The two interior beam-column subassemblages were designated VI (to be repaired with vacuum impregnation) and PI (to be repaired with pressure injection). Following repair, the models were designated RVI and RPI, respectively, for the subsequent tests of the repaired structures. The dimensions of the models and cross-sectional details are given in Figure 1.

An interior beam-column subassemblage was chosen for the test specimen because of the severe anchorage demands imposed upon the joint when subjected to lateral loading. A simultaneous condition of tension and compression exist in the reinforcement on opposite faces of the joint. The resultant forces tend to drive the reinforcement through the joint if adequate anchorage is not available.

ACI-ASCE Committee 352 (Ref. 5) recommends a minimum column depth to bar diameter ratio of 20 for joints located in seismic regions. In this test, No. 8 bars were used as the longitudinal beam reinforcement which would require a 20 in. (500 mm) column width according to the aforementioned recommendations. The 15 in. (380 mm) column width of the models created a severe anchorage condition in the joint region. This was done to compare the relative effectiveness of the techniques in restoring bond.

Material Properties The nominal material properties were 6000 psi (41 MPa) for the concrete compressive strength and 60 ksi (410 MPa) for the reinforcement yield stress. The average measured concrete strengths were approximately 9400 psi (65 MPa) and 8800 psi (61 MPa) for VI and PI, respectively. The actual yield stress of the No. 8 longitudinal beam reinforcement was 80 ksi (550 MPa).

Epoxy The epoxy used in the tests was Adhesive Engineering Epoxy 1548. This epoxy was chosen because it exhibited the best overall characteristics in terms of moderate viscosity (2.4 poise), an 80 minute pot life which allowed sufficient working time for the vacuum impregnation technique, and it was stable when set in small or large quantities which was also a concern for the vacuum impregnation test. A less viscous (1.4 poise) epoxy, Epoxy 1468, would typically have been used for the pressure injection test; however, it was desired to use the same type of epoxy for both techniques to facilitate comparison of the results.

Load History A series of static cyclic loads were applied to the structure. The peak values corresponded to displacement ductility factors (DDFs ≡ ratio of beam end displacement to theoretical beam end displacement at yield) of three cycles at 1.3 (1.0), two cycles at 1.0 (0.5), two cycles at 4.0 (4.0) and three cycles at 2.2 (2.2); where the numbers given in parentheses indicate the DDFs for the negative half cycles.

DESCRIPTION OF REPAIR PROCEDURES

Pressure Injection Technique The area around the cracks was brushed and compressed air was blown into the cracks to remove any loose particles. Small strips of tape were placed at approximately three locations along each crack on the side of the beam: near the bottom, middepth and top of the beam. A quick-setting viscous epoxy was then applied across all of the cracks in approximately 2 in. (50 mm) strips. After the epoxy set over the cracks, the tape strips were removed to serve as ports for injecting epoxy. The epoxy was first injected at the lowest port along each crack. When the epoxy emerged from the next highest port, the lowest port was plugged, and the pressure injection proceeded to the next highest port. This procedure was continued for each successive crack along the beam.

Vacuum Impregnation Technique The entire region to be repaired was first covered with a plastic mesh which provided a path for the epoxy to flow around the surface of the specimen when the vacuum was drawn. The area was then covered with a 10 mil (0.3 mm) polyethylene sheet. Epoxy inlet ports were located at three locations along the bottom of the beams. A hose was connected from the top of the repair region in the column to a vacuum source (intake valve of a 250 cfs (7.1 m^3/sec) air compressor). The procedure is shown in Figure 2: 1) Inlet ports are sealed and a vacuum is drawn on the system. 2) Epoxy is introduced in the system until the specimen is completely submersed. 3) When the epoxy is just about to set, the vacuum is removed and the atmospheric pressure on the system forces the epoxy into any remaining voids.

A disadvantage of the pressure injection technique in restoring bond is that it is difficult to repair any offshoot cracks. The pressure injection technique tends to trap air in such cracks. This is not a problem with the vacuum impregnation technique because, ideally, the entire system is evacuated.

COMPARISON OF TEST RESULTS

The test results will be briefly examined in this section for the cycles which are of particular interest: the initial cycles (Cycles 1-2) and the largest displacement amplitude cycles (Cycles 6-7). Refer to References 6 and 7 for more details.

Initial Cycles (1-2) Figure 3 shows the superimposed load-deflection histories for the first two load cycles of VI and RVI, the test of the original undamaged structure and subsequent test after it had been repaired with the vacuum impregnation technique. The peak-to-peak stiffness of RVI was approximately 85 percent of the original structure. The difference in the stiffness values may be attributed to three types of damage which were either inadequately or intentionally not repaired: 1) Small cracks less than 5 mils (0.1 mm) were not incorporated into the repair region. 2) A very large crack (0.25 in. (6 mm)) at the beam-column interface was not repaired well with this technique. After the vacuum was removed, the epoxy tended to drain out of this very large crack before it had time to set. 3) The column cover suffered spalling near the end plates due to inadequate bearing during the original tests.

Another interesting comparison is the peak-to-peak stiffness observed in the last cycle of the test of VI compared with the initial stiffness of RVI. Had structure VI not been repaired, one would expect the initial stiffness of the retest (RVI) to be the same or less than that measured in the last cycle of VI--the ratio is approximately three times larger which indicates the effectiveness of the repair technique. Similar results with respect to stiffness were obtained for the tests of PI and RPI (see comparison in Fig. 4). PI did not suffer as much column cover spalling near the end plate as VI, and the epoxy did not drain from the interface crack in RPI because the surface of the cracks were first sealed with this procedure.

Largest Cycles (6-7) The superimposed load-deflection histories for VI and RVI are shown in Figure 5 for the largest lateral displacement comparison. During Cycle 6, the stiffnesses and strengths attained by both the original and repaired structures were quite similar. As evidenced from the slight pinching of the load-deflection curves and from results obtained with instrumentation used to measure bar slippage, the bond between the reinforcement and the concrete suffered major deterioration during Cycle 7 for VI and during the negative displacement of Cycle 6 for RVI. The measurements mentioned above regarding bar slippage were obtained by attaching a stiff wire to the beam reinforcement in the joint. This wire passed through the joint in a greased tube and was connected to a linear voltage differential transformer (LVDT) at the exterior face of the joint. Movement of the reinforcing bar due to strain and bond deterioration could thus be measured. By determining the strain component of the movement with strain gages attached to the reinforcement, it was possible to ascertain the displacement component associated with bond deterioration.

Similar behavior was observed with respect to the PI and RPI tests. The maximum measured strength of RPI was slightly higher (5 percent) than PI because the hinge region was displaced from the interface in the test of RPI. This was attributed to the effectiveness of the epoxy pressure injection repair of the large crack at the interface (tensile capacity of epoxy is greater than that of concrete).

Figure 6 shows a comparison of the energy dissipation capacities observed in the tests. The comparison is made by observing the ratio of the energy dissipated by the repaired structures to that of the original structures for the first cycle to each new displacement level (1,4,6 and 8). It may be observed that in the beginning cycles, the pressure injection technique appeared to be more successful in restoring energy dissipation. The primary reasons for this are that the epoxy drained from interface crack with the vacuum impregnation technique and the column had suffered some deterioration (cover spalling) in later cycles of the test of VI which caused a reduction in the initial stiffness of RVI.

The important cycle for energy dissipation is Cycle 6. (Seventy percent of the total energy which dissipated during the test occured during Cycles 6 and 7.) This cycle is broken into two charts to indicate the positive displacement half cycle and the negative displacement half cycle, respectively. The effectiveness of the repair techniques in restoring the energy dissipation capacity may be observed in the positive direction of Cycle 6. The energy dissipation of the structure repaired with the vacuum impregnation technique actually exceeded that of the original structure during that half cycle. The reduction in the negative half cycle reflects the earlier slippage of the beam reinforcement in the repaired structures.

CONCLUSIONS

Both repair techniques worked well. The repaired structures achieved over 85 percent of the initial stiffness of the originally undamaged structures which represented a three-fold increase over the final stiffness of the original structures. In addition, the strength and energy dissipation capacities were restored in the repaired structures. The bond between the reinforcement and the concrete also appeared to be restored by the repair procedures, however, it tended to deteriorate at an earlier load cycle (Cycle 6 rather than Cycle 7) in the tests of the repaired structures.

It is recommended to use the vacuum impregnation procedure to repair large regions of damage. The entire region may be repaired at once with this procedure rather than repairing each crack individually. In these tests there did not appear to be any "offshoot" cracks in which air could have become trapped; the cracks seemed to be well-connected judging from the outflow paths of epoxy observed with the pressure injection technique. Had there been "offshoot" cracks, it is believed that the vacuum impregnation technique would be better-suited for the repair of such a situation.

ACKNOWLEDGMENTS

This research investigation was sponsored by the National Science Foundation under Grant No. NSF/ECE-8451536 and was carried out at the University of Minnesota Civil and Mineral Engineering Structures Laboratory. The advice and materials supplied by M. Paipal of Consultech and A. Gaffney of Adhesive Engineering were greatly appreciated. The authors also wish to thank L. Hagan, the Minnesota Department of Transportation, Twin City Testing, Inc., R. Sterling, C. Fairhurst, and the late J. Milne.

REFERENCES

1. Popov, E. P. and Bertero, V. V., "Repaired Reinforced Concrete Members Under Cyclic Loading," International Journal on Earthquake Engineering and Structural Dynamics, Vol. 4, 1975.
2. Mahin, S. A., "Rate of Loading Effects on Uncracked and Repaired Reinforced Concrete Members," Earthquake Engineering Research Center Report UCB/EERC-72/9, Univ. of California, Berkeley, 1972.
3. Lee, D. L., Wight, J. K. and Hanson, R. D., "Original and Repaired Reinforced Concrete Beam-Column Subassemblages Subjected to Earthquake Type Loading," Department of Civil Engineering Report UMEE 76S4, University of Michigan, Ann Arbor, 1976.
4. Shinsuke, N., Toshikazu, K. and Hidehavu, S., "A Repaired Effect of Reinforced Concrete Joint Assemblies Subjected to Loads," Proceedings of the Third Seminar on Repair and Retrofit of Structures, University of Michigan, Ann Arbor, 1982.
5. ACI-ASCE Committee 352, "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures," ACI Journal, Vol. 82, No. 3, 1985.
6. Tsai, W-J., French, C. E., "Repaired R/C Interior Joints under Cyclic Loads," Structural Research Report No. 88-04, Civil and Mineral Engineering Department, University of Minnesota, Mpls., 1988.
7. Thorp, G., French, C. E., "Comparison of Techniques to Repair Moderate Earthquake Damage with Epoxy," Master's Thesis, Civil and Mineral Engineering Department, University of Minnesota, Mpls., 1988.

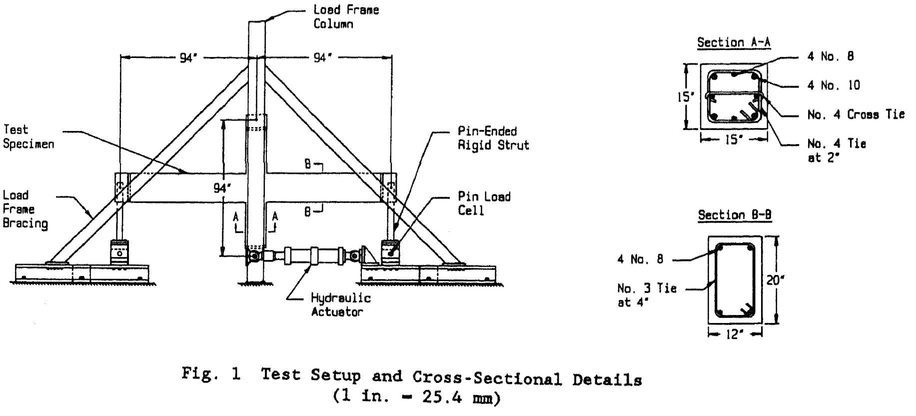
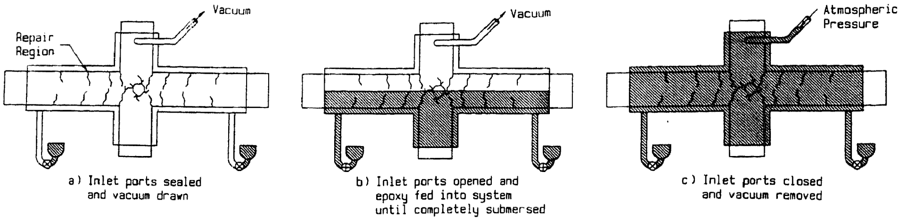


Fig. 1 Test Setup and Cross-Sectional Details (1 in. = 25.4 mm)



a) Inlet ports sealed and vacuum drawn

b) Inlet ports opened and epoxy fed into system until completely submersed

c) Inlet ports closed and vacuum removed

Fig. 2 Vacuum Impregnation Repair Procedure

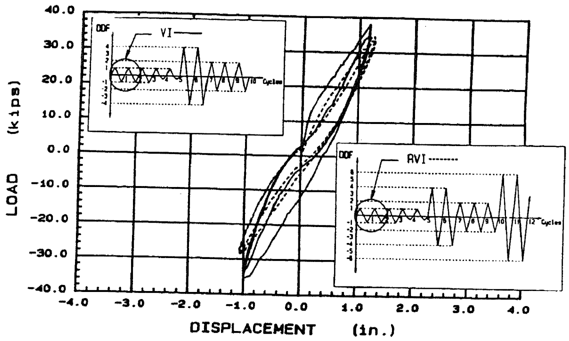


Fig. 3 Load-Deflection Response of VI and RVI - Cycles 1-2 (1 in. = 25.4 mm, 1 kip = 4450 N)

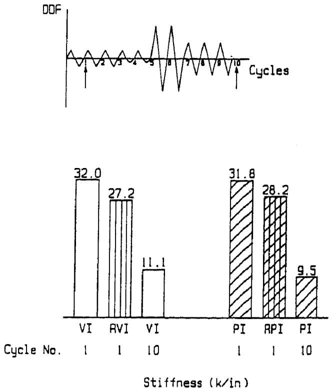


Fig. 4 Stiffness Comparison (1 kip/in. = 175 kN/m)

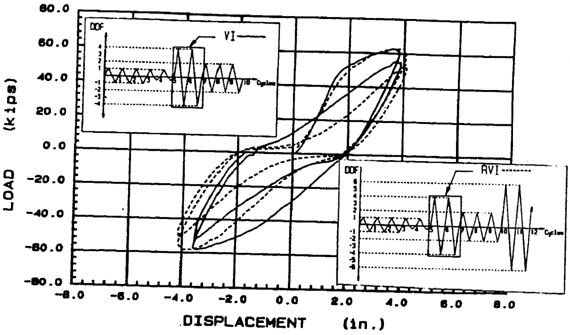


Fig. 5 Load-Deflection Response of VI and RVI - Cycles 6-7 (1 in. = 25.4 mm, 1 kip = 4450 N)

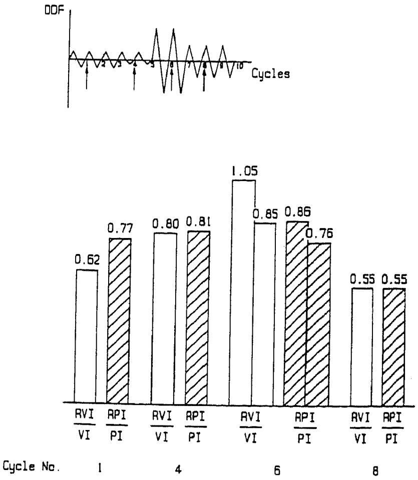


Fig. 6 Energy Dissipation Ratio of Repaired to Original Models