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REPAIR AND STRENGTHENING OF CONCRETE STRUCTURES DAMAGED BY EARTHQUAKES

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SUMMARY

The effectiveness of different repair and strengthening techniques in restoring or improving the properties of reinforced concrete components damaged by earthquake-type loading was studied. Two-bay frames and single-connection subassemblies were tested by imposing predefined displacements before and after performing repairs. Repairs by injection of epoxy resin were highly dependent on quality control. Replacing damaged concrete and jacketing members restored or improved the strength and stiffness provided both columns and adjacent beam segments were appropriately reinforced. Addition of external steel elements proved practical as well as cost effective.

INTRODUCTION

The problem of repairing and strengthening of concrete structures in earthquake prone areas has attracted the attention of many researchers in recent years. This interest is due to the existence of many buildings damaged by past earthquakes and other buildings that must be strengthened to meet upgraded building standards.

One approach to repairing structures is to restore or strengthen each damaged member and connection to the desired level. The other is to add new structural elements, such as shear walls and diagonal bracing systems that are capable of resisting most of the lateral loads. Many times, however, a combination of the two approaches will render the best solution.

This study focused on the first of the approaches mentioned above. It focused on the repair and strengthening of damaged members and connections. An experimental investigation was performed to evaluate and seek improvements to repairing techniques. Commonly used repair procedures and strengthening details as well as modifications and improvements of those procedures were tested to compare the behavior of repaired specimens with that of undamaged specimens. These comparisons were made on the basis of restitution or improvement of strength, stiffness, and energy dissipation capabilities.

The types of damage of major concern were flexural and diagonal cracks in members and joints, spalling of concrete due to compression, bond failure, and buckling of longitudinal reinforcement. The types of repair considered were injection of epoxy resin, replacement of damaged concrete, enlargement of member sections with reinforced concrete jackets, and addition of externally placed steel elements.

TEST SPECIMENS

The test specimens were in the form of beam-to-column connection subassemblies with some having a portion of the floor slab and transverse beams. Out of a total of eleven specimens, five were single beam-to-column connections and the rest were subassemblies composed of three columns connected by a beam. The details of a typical specimen are shown in Fig. 1 and a summary of the characteristics of all specimens is given in Table 1.

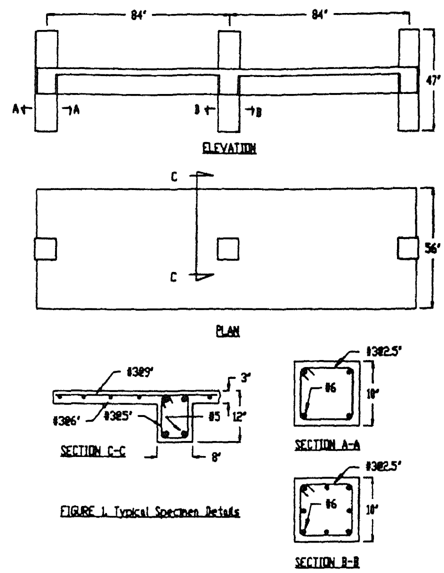

FIGURE 1. Typical Specimen Details

The test specimens were first subjected to a predefined cyclic lateral displacement routine to simulate damage conditions during an earthquake. The damaged specimens were then repaired and tested again under the same conditions. Comprehensive instrumentation was used to collect data on various aspects of the response of specimens during both tests.

TABLE 1. CHARACTERISTICS OF SPECIMENS AND REPAIRS

Specimen	Description	Repairs
CR	3 columns connected by beams	Replace damaged concrete: beams, columns
CTBR	Transverse beams added to CR	Replace damaged concrete: beams only
CS1R	Floor slab added to CTBR	Inject of epoxy only
CS2R	Similar to CS1R	Jacket columns with R/C
CS4R	Similar to CS1R	Similar to CS2R
CS3R	Similar to CS1R, plastic hinge shifted outside joints	Splice buckled bars, replace damaged concrete
ER	Single Ext. joint, no slab	Jacket column with R/C
IR	Single Int. joint, no slab	Jacket column, part of beams with R/C
ES1R	Single Ext. joint, with slab	Jacket column, part of beam with R/C
ES2R	Single Ext. joint, with slab	Add external steel, column only
ISR	Single Int. joint, with slab	Add external steel, column and beams

Note: All specimens were injected with epoxy to seal small cracks (less than 1/4 in.) before the above mentioned repairs were performed.

REPAIR PROCEDURES

The type of repairs used in each specimen was chosen on the basis of the observed damage and the desire to evaluate the procedures described above. Table 1 shows a summary of the procedures used in each case.

In general, it was conlcuded that injecting epoxy in small cracks would be an economical way to restore the strength of the existing members at least partially. For this reason epoxy injection was the first step in the repair procedures used for all specimens.

Replacement of damaged concrete was performed in three specimens. The concrete in the joints and neighboring portions of the beams was replaced in specimen CR and only the damaged parts of the beams were replaced in CTBR as illustrated in Fig. 2. In specimen CS3R, the damaged concrete in the beams and part of the slab was replaced with epoxy mortar in addition to other tasks as shown in Fig. 3.

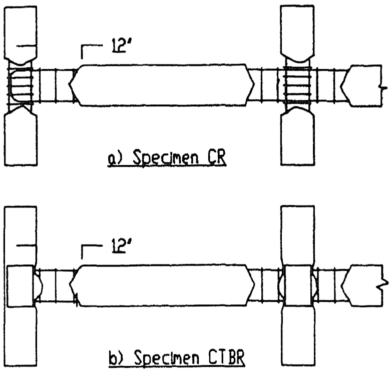

FIGURE 2. Removal of Damaged Concrete

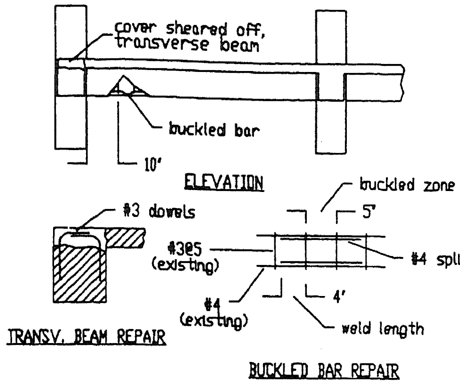

FIGURE 3. Specimen CS3R Repair Details

Where strengthening of members was desired, elements of smallest feasible size compatible with minimum clearance requirements were used. In designing the repairs, it was ensured that the strength of the reinforcements in each member was at least as much as that of the undamaged member.

Since strengthening of columns is a common practice in repair projects, some of the specimens were repaired by strengthening the columns only. It was felt, however, that connections would perform better if beam segments adjacent to the joints were also reinforced. This form of repair would have the added advantage of moving the zones of most likely damage away from the joints. Fig. 4 and 5 show the details of reinforcement used in specimens where only the columns were reinforced and those where beam segments were also reinforced, respectively.

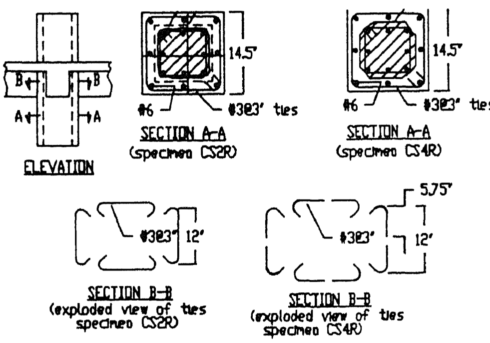

FIGURE 4. Jacketing of Columns (specimens CS2R, CS4R)

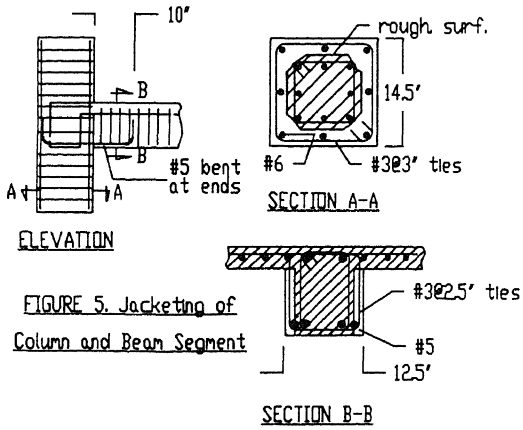

FIGURE 5. Jacketing of Column and Beam Segment

Addition of externally applied steel elements as a method of reinforcing columns has been implemented in actual repair projects in the past with less than satisfactory results (Ref. 1) due to problems with transmission of stresses through the joints. For this reason the details shown in Fig. 6 were developed for specimens ES2R and ISR with the specific purpose of addressing the problem of transmission of stresses through the joints.

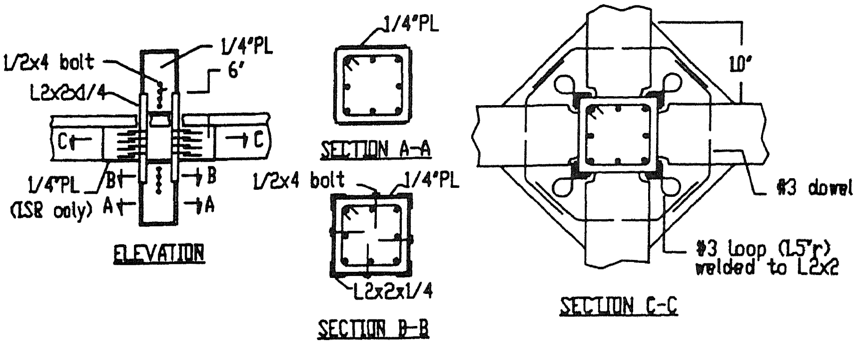

FIGURE 6. External Steel Reinforcement
(specimens ES2R, ISR)

TEST PROCEDURE

The two-bay frame subassemblies were tested in a steel reaction frame schematically shown in Fig. 7. The columns were pin-connected at the top to a beam capable of horizontal movement. A single actuator was used to impose the displacement history, shown in Fig. 8, at the top ends of the columns. The bottom ends of the columns were connected to hinges that rested on jacks capable of applying axial loads to the columns. Single-connection subassemblies were tested in a similar manner except that the beam ends were hinged to vertical links capable of allowing lateral displacement.

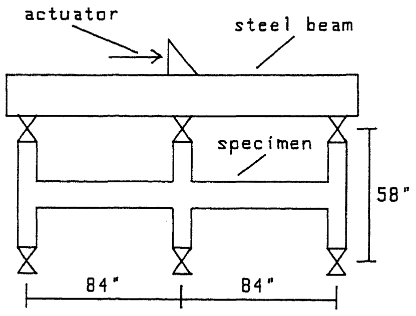

FIGURE 7. Test Setup

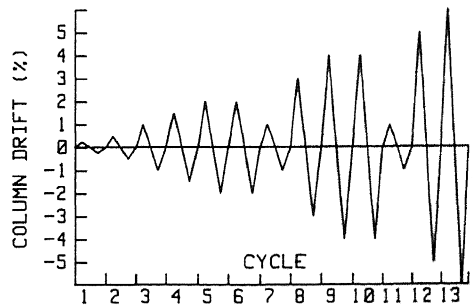

FIGURE 8. Imposed Displacements

The test sequence was automated using a computer program which imposed the specified displacements, collected and stored data at appropriate intervals and interacted with the operator during the various stages of a test. Each repaired specimen was tested under conditions that duplicated as closely as possible those under which the test before repairs was performed. The data obtained from both tests could then be easily compared.

TEST RESULTS

Epoxy Injection Specimens CS1R and CS3R were used to evaluate this repair technique. In specimen CS3R an effort was made to insure maximum possible penetration of the resin. The injection process was repeated if voids were observed after removing the surface seals.

Figure 9 shows the load vs. displacement plots of these two specimens before and after repairs. The plots are normalized with respect to load and displacement amplitudes of the first test. In both specimens the load amplitudes during the early cycles were smaller during the tests after repairs indicating a reduction in stiffness. The loops after repairs, in the case of specimen CS1R, were pinched near the zone of zero displacement. In specimen CS3R, however, the shapes of the loops after repairs were basically the same as those before repairs. The pinched shape of the loops of specimen CS1R indicates that the reduction in stiffness in this case was due to cracks that were not filled with epoxy and to slippage of reinforcing bars through the joint despite the injection of epoxy. In specimen CS3R, the epoxy mortar, which has a lower modulus of elasticity than the concrete it replaced, was the main reason for the observed reduction in stiffness. These results suggest that large variations in performance can occur depending on the quality of the injection work.

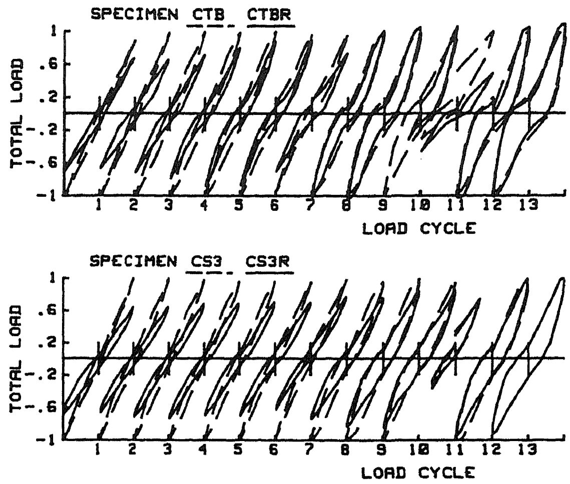

FIGURE 9. Load vs. Displacement Loops

Replacement of Damaged Concrete The data obtained from testing specimen CR after repairs showed characteristics that were quite similar to those before repairs, demonstrating that the stiffness and strength of the specimen had been completely restored. In the case of specimen CTBR, however, loss of stiffness was indicated by smaller amplitudes and significant pinching in the shapes of the load vs. displacement loops obtained during the test after repairs. This deficiency in behavior is explained by recalling that damaged concrete was replaced in the beams only, leaving the damage around the bars inside the joint intact.

Jacketing with Reinforced Concrete The columns of specimens ER, CS2R and CS4R were encased in a reinforced concrete jacket while the columns and a portion of the beams were strengthened in specimens IR and ES1R. The columns in all these specimens suffered very little damage during the tests after repairs. The cracking patterns in the beams of the first group of three specimens were similar in size as well as in location during both tests. However, in the last two specimens most of the damage in the beams was concentrated in regions where the added longitudinal reinforcement was stopped.

The tests of the first three specimens mentioned above gave evidence of greater strength after repairs as indicated by larger load amplitudes during cycles of large displacements. There was, however, little evidence of increase in stiffness and pinching was observed in all cycles of the test after repairs. This behavior indicates that jacketing of columns alone was not effective in improving the stiffness of these specimens. On the other hand, the loops obtained from testing specimens IR and ES1R after repairs show increased stiffness throughout the test and there is little evidence of pinching even during large displacement cycles. This indicates that jacketing of columns and adjacent portions of beams was quite effective in restoring and improving the stiffness and strength of the specimens.

Strengthening with External Steel Elements This method of repair demonstrated advantages as far as execution of repairs is concerned. The reinforcing steel elements were prepared in advance in the shop and the preliminary work with the specimens was limited to drilling holes and roughening surfaces that would be in contact with new concrete. The installation of reinforcement consisted of anchoring dowels and bonding steel plates in place with a viscous epoxy resin mix, welding angles to the plates, and casting concrete around the joint. The flammability of epoxy resins can be a serious problem in such repairs and should be properly addressed and adequate protection against fire provided for the reinforcements.

The test data for specimens IR and ES1R indicates that they were stronger and stiffer after repairs even during the first few cycles. No increased pinching was observed as with some of the other specimens. The concrete reinforced by dowels cast around the joint restored stiffness and resistance to shear and compression in the region where the beam was damaged during the test before repairs. In the case of specimen IS2R, a steel plate at the bottom of the added concrete was able to transmit tension and compression forces produced by bending. Thus the stiffness and strength increased in greater proportion than in the case of specimen ES2R.

CONCLUSIONS

Based on the results of these tests, the following conclusions can be drawn:

1. Epoxy injection was found to be an economical repair method but its adequacy was highly dependent on quality control.

2. Replacing damaged concrete can effectively restore the strength of structures. Restoring stiffness using this approach would require rebuilding joints, which may not be practically feasible.

3. Encasing members in concrete jackets can effectively restore or improve the strength and stiffness of structures provided that columns and adjacent beam regions are reinforced together.

4. Using externally placed steel elements that properly address the problem of transmission of stresses through the joint is an alternative strengthening method that can be cost effective.

ACKNOWLEDGEMENTS

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