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Reparability of Reinforced Concrete Special Moment Resisting Beams

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Abstract: This paper presents the results of a quasi-static cyclic test carried out on a reinforced concrete special moment resisting beam to study the efficiency of traditional repair techniques in restoring the strength and stiffness capacity of damaged RC beams. The beam was tested in a cantilever mode and was subjected to a standard loading protocol with increasing amplitude of displacement cycles. The final damage state of the beam consisted of severe cracking and spalling of the cover concrete. The cracks were repaired with low-viscosity injection epoxy and the spalled concrete was repaired with early-strength grout. The repaired specimen was subjected to the same loading protocol as the original specimen to study the efficiency of the repair technique employed. It was observed that epoxy injection is not effective in restoring the strength and stiffness of beams with bar slip of longitudinal bars at the support end.

Keywords: *Reinforced Concrete, Reparability, Epoxy Injection, Strength, Stiffness, Bar Slip*

Introduction:

Modern seismic design codes [1-3] design buildings with the objective to avoid collapse and save human lives. Structures are designed for seismic forces that are considerably smaller than the design-level forces, and therefore they are prone to damage during large earthquakes. Reinforced concrete special moment resisting frames are designed according to the principles of capacity design; which states that damage should be concentrated at fixed locations in beams, often called plastic hinges. The plastic hinges are located at the ends of beams and should be proportioned and detailed to respond primarily in flexure mode rather than brittle modes of response such as shear. This philosophy forms the basis of almost all the modern seismic design codes [1-3]. However, the subject of reparability of damaged reinforced concrete structures, after being subjected to an earthquake, has been addressed rarely. The performance of reinforced concrete moment resisting frames, designed to modern codes, in the recent earthquake of Christchurch (2011) was satisfactory but raised the issue of reparability of reinforced concrete structural components [4]. A large number of damaged reinforced concrete frames had to be demolished due to the lack of sufficient experimental evidence to justify the use of traditional repair techniques in restoring the capacity of damaged reinforced concrete structural elements.

This paper addresses the issue of reparability of reinforced concrete structural elements through an experimental program. Quasi-static cyclic testing was conducted on a special moment resisting beam to study the efficiency of epoxy injection and grout patching in the restoring the strength and stiffness of a damaged beam.

Experimental Work:

The cross sectional dimensions of the beam are 12in. x 18 in. with a length of 96 in. The beam had 3-#8 bars in the top and bottom layer giving a longitudinal reinforcement ratio of 1.26%. The transverse reinforcement was provided according to the confinement requirements of ACI-318 for beams.

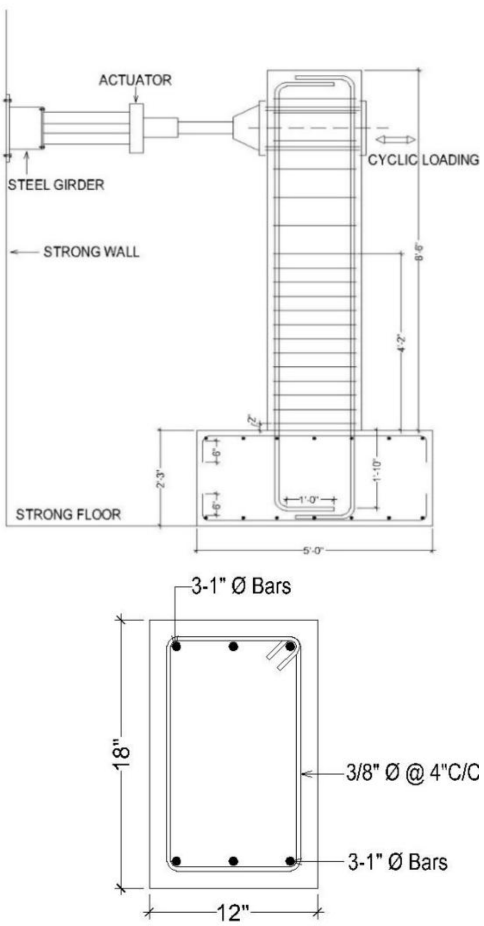

Figure 1: Specimen Reinforcement Details

Materials:

Steel:

The longitudinal and stirrup reinforcement consisted of ASTM-A615 grade-60 bars. Steel coupons were tested in tension for the #8 and #3 bars to test their yield strengths. The details of tests are given in the Table 1.

Table 1: Reinforcement Steel Tension Test Results

S. No	Nominal Dia	Yield Strength (Psi)	Ultimate Strength (Psi)
1	1.000	66140	91846
2	1.000	69837	95056
3	1.000	64612	89985
7	0.375	77939	107313
8	0.375	67006	92291
9	0.375	71171	99639

Concrete:

Normal weight concrete with a specified strength of 3000 psi was used for all the beams. The concrete mix design ratio used was 1:2.13:3.61 with a water-to-cement ratio of 0.57. Standard cylinders of 12 in. height and 6 in. diameter were tested under compression loading to validate the mix design. The results of compression tests on the cylinders are given below in Table 2.

Table 2: Concrete Compression Test Results

Specimen ID	Age of Concrete (days)	Concrete Compressive Strength, fc' (psi)
28-1	28	3282.22
28-2	28	3204.25
28-3	28	3492.72

Specimen Construction and Setup:

The specimen was cast using plywood formwork and were cured for a total of fourteen days. The beams cantilevered out of an anchorage block which was anchored to the strong floor of the laboratory using bolts Figure 2. The lateral load was applied at some distance from the free end of the beam using a manual-controlled hydraulic actuator. The actuator was attached to the beam using a hinge assembly to allow the rotation of the actuator Figure 2.

Figure 2: Specimen Construction & Setup

Loading History:

The loading protocol used consisted of a series of increasing displacement cycles with three cycles per each displacement increment. The control point for the displacement amplitude was the point of application of load by the actuator.

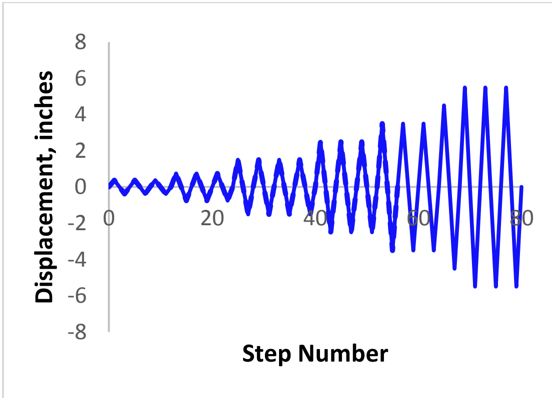

Figure 3: Loading Protocol for Testing

Test results:

Damage Description and Hysteretic Response:

The specimen was loaded with an initial displacement of 0.375 in. Full depth flexural crack formed at the northern face of the beam at a distance of 18 in. from the face of the block, whereas a flexural crack at a distance of about 16 in. formed on the southern face. Cracking was not observed on the eastern and western faces at this displacement demand. At a displacement amplitude of 0.75 in., no new cracks formed on any face of the beam. With further increase in displacement demand to 1.5 in., new flexural cracks formed at 8 in., 13in. 26 in. and 34 in. from the support on the southern face. A flexure crack formed at northern face at a distance of 27 in., whereas slight diagonal cracking occurred on the western face. A wide distribution of cracks took place during the displacement cycles of 2.5 in., with cracks on the northern and southern faces as high as 54 in. Full depth inclined cracks were observed on the eastern and western faces of the beam which increased in number at displacement demand of

3.5in. Minimal new cracks were observed further till the conclusion of test at 5.5 in.

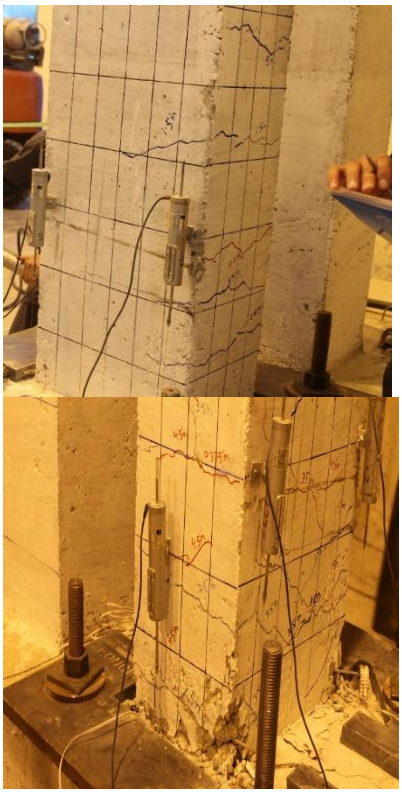

Figure 4: Specimen Damage Patterns

Spalling of the concrete cover started on the northern and southern faces at a displacement of 4.5 in., which escalated at final the displacement cycles of 5.5 in exposing the reinforcing bars on the southern face. The specimen could not be displaced further because the maximum stroke of the hydraulic jack was 6 in. The hysteretic response was marked by a strong pinching due to the slip of longitudinal bars. No strength drop was observed in the hysteretic response due to the fact that the specimen was not tested till failure as shown in Figure 5.

Repair of Damages:
The main objective of conducting this tests was to study the reparability of reinforced concrete beams damaged by seismic loading. Since the specimen did not sustain damage beyond spalling of cover concrete, therefore, the repair techniques chosen were epoxy injection into cracks and patching of spalled concrete. The epoxy used was a low viscosity injection epoxy. The patching of spalled concrete was done using non-shrink and early-strength grout.

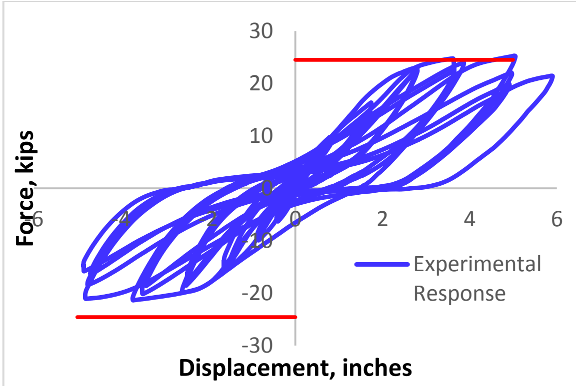

Figure 5: Hysteretic Response

Figure 6: Epoxy Injection and Patching of Spalled Concrete

Damage Description and Hysteretic Response:
The response of the repaired specimen was unsatisfactory. The beam showed a considerable drop in the strength and a severe pinched hysteretic response due to loss of stiffness Figure 7.

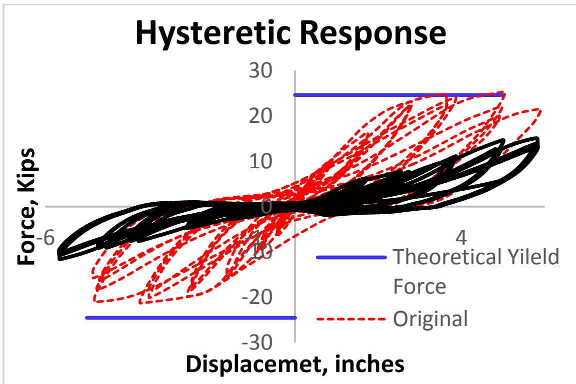

Figure 7: Comparison of Original & Repaired Response of Spectrum

The reason behind this performance is the fixed end rotation at the interface between the beam and the anchorage block. The interface opening was injected with epoxy but based on the results it can be said that the merely filling the interface opening with epoxy will not restore the original stiffness of the beams which will render the beam unable to achieve its original strength. The efficiency of the epoxy injection in treating the cracks could not be studied due to the fact that the beams did not sustain the original loads which caused those cracks.

Conclusions:

i. The damage of the test specimen consisted of cracking, spalling and fixed-end rotation due to slip and inelastic extension of longitudinal bars. The cracks of the plastic hinge region and the interface crack (due to fixed-end rotation) were both injected with low viscosity epoxy to restore the capacity of the beam. It was, however, observed that the strength and stiffness of the beam were not regained because epoxy did not restore the bond between concrete and steel.

ii. Therefore, it is concluded that the repair of reinforced concrete beams, with fixed-end rotation, will be ineffective by mere filling of interface crack with epoxy. The significant loss of strength and stiffness due to fixed-end rotation also renders the repair of the rest of the damaged beam useless.

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