CONCRETE NZ CONFERENCE
2019 Concrete for life

EPOXY RESIN INJECTION AS A REPAIR STRATEGY FOR CONCRETE

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SUMMARY
BMC carried out a literature review on epoxy resin injection (ERI) to determine the efficacy of ERI as a repair strategy for reinforced and unreinforced concrete. BMC concluded that ERI, when carried out using appropriate quality assurance measures, optimum placement method, and an appropriate product, is an effective means of repairing reinforced and unreinforced concrete structural elements. ERI was found to reliably reinstate stiffness and durability. Strength and energy dissipation were largely not influenced by the repair because they are dependent on the condition of the reinforcement, which cannot be altered with ERI.

INTRODUCTION

<u>Background and Economic Context</u>

Properly designed and implemented epoxy repair strategies can, and in many instances do, provide a compellingly cost-effective alternative to demolition and reconstruction of structures moderately damaged by earthquakes. If cost was not a factor and resources were unlimited, most owners would understandably prefer to replace the old and damaged with something new and fresh. However, as has been reported [1] [2], many insurers and underwriters have indicated that they will have no choice but to limit their presence, or in some cases abandon the New Zealand marketplace for natural disaster cover in the future, as they face insolvency if an earthquake sequence producing damage similar to or worse than that which resulted from the 2010-2011 Canterbury Earthquake Sequence (CES) occurred, and more cost-effective repair strategies cannot be found and broadly pursued. Already, reinsurance costs and premiums have increased and many building owners have found that insurers are reluctant or unwilling to provide standalone earthquake cover for buildings of certain ages or in certain areas. These outcomes are not in the public interest, having a detrimental economic and social effect on society. An engineer's charter is to restore and improve the resilience of our cities and communities as cost-effectively as possible.

Members of our professional body, Engineering New Zealand, are bound by our Code of Ethical Conduct [3], which includes a number of obligations in the public interest, including acting sustainably, so that we meet the needs of the present without compromising the ability of future generations to meet their own needs (Rule 2) and reporting adverse consequences (Rule 3). We are also required to conduct ourselves in a professional manner, including obligations to act competently (Rule 4) and behave appropriately (Rule 5). The latter is described as a requirement to *"act with honesty, objectivity, integrity, and treating people fairly and with respect."* Good judgement and decision making are central to ethical practice. If we want to maintain our reputation as a profession and make a meaningful contribution in this field, engineers need to demonstrate ethical competence in how we make decisions on the complex technical issues surrounding insurance claim repairs.

Acting sustainably is addressed in 'Rule 2' and is an important consideration when assessing repair options versus demolition to meet structural or insurance repair requirements. Construction and demolition waste make up a significant portion of total landfill contributions. Recycling demolition waste typically requires more energy input than its market value/benefit.

Scope

A review of literature regarding epoxy repair was conducted to determine the efficacy of epoxy resin injection as a repair strategy for damaged reinforced and unreinforced concrete. The term 'damaged concrete' forms a spectrum based on the extent of damage. On one end of the spectrum is 'light' damage comprised of hairline cracks. On the other end of the spectrum is a 'basket of rubble' loosely contained within a reinforcement cage. Through this literature review, BMC sought to determine if epoxy resin injection is an appropriate repair technique and, if so, what portion of the spectrum of damaged concrete it is appropriate for.

Epoxy and Injection Techniques

Epoxy Placement Techniques

Pressure injection and vacuum impregnation are considered in this report. The relative efficacy of pressure injection versus vacuum impregnation was researched by French *et al*. [4]. Results indicated that vacuum impregnation may be more effective for larger sections, sections with offshoot cracks, and hairline cracks at the crack formation boundaries/limits. BRANZ [5] recommends vacuum impregnation for cracks adjacent to areas susceptible to delamination to mitigate the injection pressure within the crack created during repair.

Determinant Repair Factors

Moriconi *et al*. [6] found viscosity and elastic modulus were not necessarily the key factors to consider when selecting an epoxy resin or when assessing the performance of a repair. Viscosity strongly impacted the effectiveness of injection for narrow cracks (those less than 0.3 mm), but was found to be insignificant for crack widths over 0.8 mm. Test results indicate that a viscosity over 400 mPa*s is less effective in restoring the mechanical properties of the injected specimen for crack widths less than 0.15 mm. Concrete microstructure and porosity were notable factors regardless of crack width. Injection cracks in porous concrete resulted in increased strength due to the epoxy spreading into the surrounding concrete. To quantify the effect of porosity, tests were completed on small reinforced beams. The repaired specimens were artificially cracked and repaired using epoxy. Results of the repaired specimens were compared to undamaged specimens. The results indicated that for fully compacted concrete, epoxy injection restored the integrity of the concrete and the flexural strength was the same. For the partially compacted specimen, a 66% increase in strength was noted and a 233% increase in strength for uncompacted specimens. More voids were originally present and subsequently filled during the repair of the uncompacted concrete creating an effective increase in the tensile capacity of the specimen resulting in an increase in flexural strength.

French *et al*. [4] suggested through their research that the wettability of epoxy was also important to consider. Epoxy with good wetting characteristics have low surface tension and spread over a surface with relative ease [7]. Wettability was regarded as significant especially for small crack widths and the reinstatement of bond between the concrete and reinforcement.

Epoxy as a Repair for Unreinforced Concrete and Masonry

Research investigations using unreinforced concrete as well as unreinforced masonry (URM) is considered in this section. Research using only unreinforced concrete was limited, thus URM was also considered. In this section, the efficacy of epoxy repair is investigated as to its ability to fill voids (reinstate shear transfer across a crack) and reinstate bond between cementitious materials. Since unreinforced concrete, particularly low-strength concrete, has minimal tensile capacity, structural elements comprised of this material have minimal capacity to act in flexure and their 'flexural strength' is not considered explicitly in the repair imperative. Structural elements such as unreinforced foundations transfer load to the supporting subgrade through compression struts and shear transfer. Thus, the repair imperative is reinstatement of shear transfer (aggregate interlock) and filling gaps to reinstate the compression capacity.

Minoru *et al.* [8] performed tests on unreinforced concrete beam specimens to evaluate the bond properties of various repair materials and determine the effect substrate roughness has on bond between concrete and and the repair material. For all epoxy repaired specimens with a rough crack surface, the maximum load, flexural bond strength, and fracture energy was greater than the "uncracked" control specimens. Additionally, the repaired specimens did not crack in or directly adjacent to the repair.

Static and dynamic compression tests to assess shear capacity were conducted on epoxy repaired masonry components by Plecnik *et al*. [9]. The tests considered epoxy repair in block specimens, block joints, and grout sections with cracks ranging between 0.5 mm and 2.5 mm. From the test results, the authors concluded that with appropriate selection of epoxy and ensuring complete penetration of the crack, the repaired structural component reached equal or greater compressive and shear strengths compared to the original specimen. Additionally, the researchers noted that in the block joint tests, due to the porosity of the mortar and consequential absorption of the epoxy, the compressive strength of the repaired sections was greater than the original 'undamaged' sections.

A review by ElGawady *et al*. [10] was conducted to summarize current research regarding the ability to repair and/or retrofit unreinforced masonry using epoxy injection. The review concluded that walls retrofitted by means of epoxy injection demonstrated a stiffness increase of 10-20% and a lateral resistance of 2-4 times that of the original resistance. One of the documents included in the review, specifically tested the ability of an epoxy resin injection repair to restore the shear strength to a value equal to or greater than the original strength of an undamaged wall. This report also addressed critical repair technique considerations noted during the tests, which include careful detection of all cracked zones and a warning to thoroughly consider the impacts on other structural elements if the injected element has a dramatic increase in strength relative to its original condition. After the original walls were tested, they were repaired with cementitious grout or epoxy resin injection. The strength of the walls repaired using epoxy resin injection increased to the extent that tests were halted because the limits of the reaction system for the horizontal force had been reached. The results indicated that the repaired walls had 2.15 and 3.91 times the shear capacity of the original walls and the initial stiffness increased slightly. When the tests were stopped, cracking was not observed in the repaired zone at the centre of the panels.

Epoxy as a Repair for Reinforced Concrete

Research investigations testing assemblies constructed for laboratory purposes and for building construction were reviewed and a summary of the results and discoveries related to epoxy resin injection are presented below. Test assemblies included beam-column subassemblies, beams, bridge girders, and bridge columns.

Conclusions Based on Building Lab Assemblies

Marder [11] focused his research on moderately damaged plastic hinges, with an emphasis on the response of typical plastic hinges in modern moment frame structures (refer to Figure 1). Moderate damage does not include crushing of core concrete or buckling of reinforcement. A beam was chosen, because it is the primary location of plastic hinging for the strong-column-weak-beam mechanism of capacity design. Repair methods utilized include epoxy injection of cracks and patching of spalled concrete. The maximum residual crack widths in specimens prior to repair ranged from 2.5 mm to 3.5 mm. Results indicate that the strength and deformation capacity of plastic hinges with modern seismic detailing are often unreduced as a result of moderate earthquake induced damage. Regarding stiffness, the initial secant stiffness to yield (defined as 0.8Mn; Mn being the nominal flexural strength of the beams calculated in accordance with NZS3101:2006) was compared. The test results indicated that most of the stiffness was restored by repairing the specimens with epoxy resin. In repaired specimens, the cracking was generally more distributed; cracks over 0.2 mm in width developed up to an average distance of 540 mm from the beam-joint interface. A shift in the plastic hinge zone, however, was not observed. Damaged concrete repaired with epoxy typically displayed a greater bond than normal concrete, meaning that epoxy injection was generally effective in keeping cracks closed. The author also found that the deformation capacity of the repaired beam was equivalent to the deformation capacity of an undamaged beam.

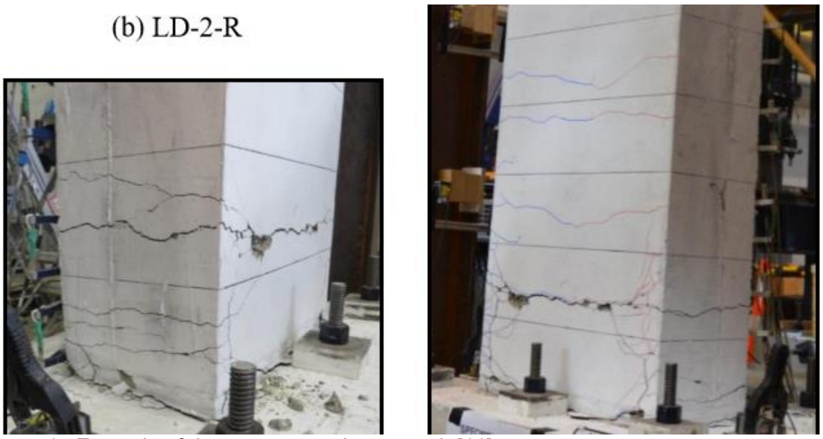

Figure 1: Example of damage state prior to repair [11].

Tsonos [12] conducted tests on beam-column joint specimens designed to the then-current Eurocode and ACI 318. The specimens were tested under reverse cyclic loading to represent strong earthquake ground motions generating severe damage states (refer to Figure 2). Specimens were repaired using epoxy pressure injection and tested using the same displacement history. The results were analysed to determine the efficacy of the epoxy pressure injection technique at restoring stiffness capacities. The author expressed concern as to whether the damage area would move because of the higher strength repair material used. The original specimens developed plastic hinges with severe cracking near the fixed end of the beam (adjacent to the column) and large strain in the beam’s longitudinal reinforcement. Additionally, anchorage failure of the beam reinforcing bars and consequential spalling of the exterior joint face occurred in one specimen during the last three load cycles. To repair the specimens, high strength mortar or epoxy resin paste was applied to areas with spalled or crushed concrete and cracks were sealed and then injected with epoxy resin. The failure modes of the repaired specimens were similar to the original, with one specimen developing a slightly more preferable failure mode than the original. The areas of damage did not shift from the beam fixed end and results indicated that the beam-column joint areas continued to remain elastic. Also, cracks repaired with epoxy injection generally did not re-crack; new cracks developed adjacent to repaired cracks. Typically, the repaired subassemblies achieved similar strength, stiffness, and energy dissipation capacities.

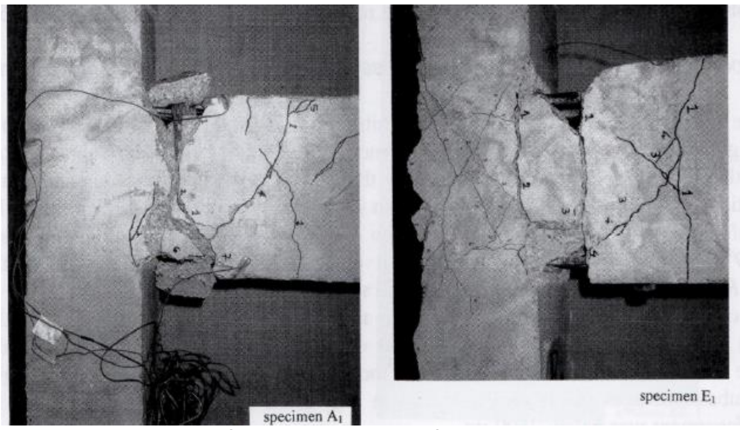

Figure 2: Images [12] of the subassemblies after the original tests illustrating the extent of damage to be repaired.

Provided in the report by Karayannis *et al*. [13] are the results from testing 17 beam-column joint subassemblies before and after epoxy crack injection. Specimens were tested to severe damage states prior to repair (refer to Figure 3). Epoxy repair was undertaken by sealing all visible cracks except for where injection ports were located, injection of low-viscosity (200-300 mPa*s) epoxy resin, and allowing the epoxy to harden for a minimum of six days before testing. Bond deterioration is indicated by the shape of the load vs. deflection plot. Pinching of the hysteretic response is indicative of severe bond deterioration. Pinching was observed in later load cycles for the repaired specimens compared to the original. A large variation was noted regarding the ability for epoxy repair to reinstate the tangent stiffness of the assembly. Data was collected both before and after the repair for the 1st, 3rd, and 10th loading cycles. Results indicated that the repairs were able to reinstate 72% - 139% of the mean stiffness of the original. Variations were attributed to the level of damage experience by the joint and the degree of epoxy penetration through the joint.

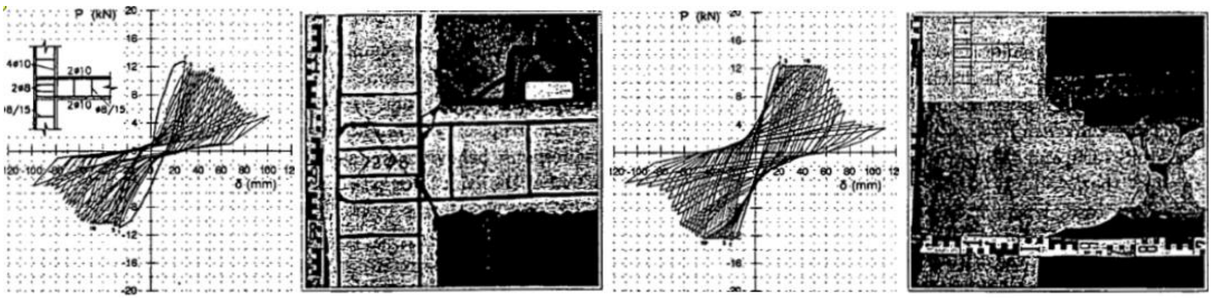

Figure 3: Excerpt [13] showing the hysteretic response and damage from one of the beam-column joint subassembly tests. Failure mode-A (observed in the initial, undamaged test) is cracking in the joint and beam end, with most of the damage localized at the end of the beam. Mode-C (observed in the repaired, post damage test) is cracks in the beam region out from the repaired region followed by spalling of the concrete.

French *et al*. [4] studied epoxy resin injection as a repair strategy for reinforced beam-column subassemblies with particular interest given to the results indicating whether stiffness and bond could be restored for the specimens. Both pressure injection and vacuum impregnation were investigated. Large reinforcement bars were intentionally selected for the main reinforcement in the beams and columns, #8 and #10 bar (25.4 mm and 32.3 mm respectively), in order to create a condition that would provide quantifiable results regarding the two technique's ability to restore bond. The repaired assemblies achieved 89% and 85% of the original specimen's initial stiffness. Differences were attributed to cracks under 0.1 mm not being repaired, spalling of column cover concrete due to inadequate bearing of the end plates, and quality control issues when repairing the subassembly using the vacuum impregnation technique because the crack was wide. The authors states that both epoxy repair techniques were effective in restoring stiffness to the specimens as the stiffness of the repaired sections were 2.5 – 3 times greater than the stiffnesses observed in the final load cycles of the specimen prior to repair. Cycles with the largest lateral displacements were assessed to determine the effectiveness of the repair techniques in restoring bond. Bond was measured using slip wires on the bar and linear variable differential transformers. Load versus slip plots were flattened, indicating where reinforcement slipped instead of picking up load. Severe bond deterioration occurred one half-cycle earlier in the repaired specimens concluding that bond was reinstated effectively. Flattening of the slope plots (indicating severe bond deterioration due to the reinforcement moving instead of the concrete transferring load to it) was observed in the 7th cycle for the original specimens and end of the 6th cycle for repaired sections.

Ekenel *et al.* [14] conducted monotonic, 4-point bending tests on four small reinforced concrete beams using an epoxy resin injection repair strategy. Two specimens were maintained under laboratory conditions while two were subjected to freeze thaw cycles, extreme temperature cycles with UV light exposure, and relative humidity cycles. Results indicated that the epoxy injection was less effective when subjected to variable environmental conditions, although all repaired specimens performed better than the control specimen. The specimens maintained in a controlled laboratory environment had an increased initial stiffness and injected cracks did not reopen. The environmentally conditioned specimens had a lower stiffness than the laboratory specimens (still higher than the control specimen) and injected cracks reopened.

Thermou and Elnashai [15] reviewed repair techniques for reinforced concrete buildings and considered global objectives of the intervention process. The researchers noted similar observations as other reports including the effectiveness of the repair process depends on the depth of penetration into the crack. Typically, cracks resulting from flexure and shear provided largely unobstructed paths and consistent restoration stiffness and shear strength in concrete-to-concrete joints. Longitudinal cracks, often resulting from bond failure, were generally discontinuous which proved problematic when repairing the steel-to-concrete bond. Epoxy resin is recommended for cracks up to 5-6 mm wide. For larger crack classified as 20 mm or less, a cement grout is deemed appropriate. With regard to global objectives, epoxy resin injection is considered to be an appropriate method for reinstating the structural characteristics of a member without appreciably diminishing the global response of the structure.

<u>Conclusions Based on Bridge Lab Assemblies</u>

Lehman *et al.* [16] conducted tests on reinforced concrete columns conforming to modern bridge requirements for regions of high seismic risk. A “moderately damaged” column was repaired using epoxy resin injection and cover replacement. Upright columns were tested with a constant axial load of 654 kN (an axial stress of 2.24 MPa) and a cyclic lateral load applied under displacement control using a servo-controlled hydraulic actuator. Damage prior to repair was classified as moderate because no spirals had fractured and longitudinal bars had not buckled or fractured. Outer longitudinal bars had yielded and the measured maximum strain in those bars was 0.03. The repaired column was tested through displacement cycles of 7.3% drift and results were compared to another column used for a “severe damage” test, but was designed and constructed the same as the column repaired with epoxy injection. Separation of the patching material followed by buckling of longitudinal reinforcement and fracture of the spiral reinforcement occurred during the 5.2% drift cycles. Longitudinal bar fracture, resulting in a loss of strength over 20% of the maximum strength, occurred during the second cycle to 178 mm. Strength and deformation capacities were not lost. Results indicated that the repair did not fully reinstate the stiffness. The lateral load capacities after the 3.125% drift cycle, which was the maximum damage cycle seen by the repaired specimen prior to repair, were the same as the original specimen for each corresponding cycle. The difference in stiffness was largely attributed to the damage initially incurred by the concrete and the inability for epoxy to penetrate all significant cracks since the applied axial load had closed up many cracks to the point where the efficacy of epoxy repair was reduced.

Smith [17] conducted tests on five full-scale reinforced concrete deck girders designed using typical 1950’s detailing to investigate the efficacy of epoxy resin injection as a repair strategy for shear cracks. Cracks were injected with an ultra-low viscosity epoxy. Results indicated that the shear capacity increased slightly, the loads at which cracks formed increased, the serviceability stresses measured in stirrups were reduced, and repaired cracks did not reopen. Four girders were repaired while variable dead loads, axial loads, and/or live loads were applied. The author found that the application of a dead load while repairing the girder generated the greatest improvement, likely because the diagonal cracks were "propped open", allowing for deeper penetration of the epoxy.

Conclusions Based on Extracts from Buildings

Two H-units were extracted from the Clarendon Tower in order to investigate the effectiveness of repair strategies for earthquake-damaged buildings [18]. Restrepo's Unit 4 was used as the 'when new' test results for the Clarendon Tower as the Tower was reputedly the prototype for Unit 4. Results from the Unit 4 test were scaled to reflect the likely result of the Clarendon Tower assemblies. The testing was completed to determine whether the structural integrity of the Clarendon Tower could have been restored through standard repair techniques. One specimen with more significant damage was repaired using a more extensive methodology. The other specimen experienced minor to moderate damage and was repaired with epoxy injection only. A gravity load similar to the expected building load for the respective locations was applied to the columns during testing. Results indicated similar yield drifts, greater relative strength of the repaired assemblies, and similar strength degradation and hysteretic pinching for the epoxy repaired assembly and Unit 4. A direct stiffness comparison doesn't appear reasonable because of the likelihood of differing loading protocols and boundary conditions. The Clarendon Tower extracts were tested using a cyclic loading protocol intended to replicate earthquake shaking as closely as possible whereas Restrepo's loading protocol appears to include a concentration of small displacement load cycles. Higher strength results for the epoxy repaired assembly were largely attributed to strain aging of the longitudinal reinforcement. The performance of the epoxy repaired assembly was concluded to be roughly equivalent to how it likely would have performed if tested prior to being damaged in the Canterbury Earthquake Sequence, demonstrating that the assemblies could be repaired to a similar or enhanced strength capacity without reducing the displacement capacity.

Durability and Applicability of Epoxy Repair

Repair strategies to address the durability of steel reinforcement must be considered. Repair using epoxy resin injection is particularly beneficial for restoring the durability of reinforced concrete elements exposed to corrosive environments. Epoxies are highly resistant to attacks from acid, alkalis, and solvents [19] allowing for the reinstatement of protection for the reinforcement. The effectiveness of epoxy resin is dependent on the bond established between the concrete and epoxy. S. Ahmad *et al*. [20] notes that if cracks are actively leaking, this will impede the epoxy from bonding well with the concrete. Special techniques using polyurethane or methacrylic acrylate resins have been developed and used with success to seal leaking cracks. Both of these resins are considered to have low strength and should be used only to resolve water leakage issues prior to using epoxy resin for structural repairs.

Effects of Fire on Epoxy Resin

In tests by Khalil [19], specimens were heated in a room at 70°C. When removed, the core temperature was 62°C. The specimens were tested in flexure. For tests done on uncracked and cracked concrete beam specimens, the ultimate load capacity was reduced by 17% - 24% due to the increase in temperature from 20°C. Beam specimens repaired with epoxy varied based on the epoxy used, ranging between 32% - 75% reduction in capacity. Plecnik *et al*. [21] studied the behaviour of epoxy repaired reinforced concrete beams under fire conditions. They concluded that the strength reduction in repaired elements is dependent largely on fire protection coatings, the thermal gradient, and type of cracks. For flexural tests on small-scale beams, failure generally occurred in regions away from the epoxy repaired areas for temperature below 93°C and at epoxy repaired areas for temperatures above 93°C. The ability to reinstate strength and stiffness of elements with shear related cracks is directly proportional to the mechanical properties of the epoxy, which are negligible above 204°C.

The author notes that for flexure, if the tensile strength of the epoxy (and concrete) is a key load path, then fire warrants consideration. Alternatively, if the reinforcement provides the tensile load path, then fire effects on the member are as they would be regardless of the epoxy repair. For shear transfer, where aggregate interlock has been reinstated by epoxy injection, fire protective coatings are required to preserve the integrity of the epoxy repair.

Literature Summary

Year	Ref.	Reinf.	Specimen	Pre-repair Drift	Loading	Strength	Stiffness
1990	[4]	Y	B/C Assembly	4.6% drift	Static Cyclic	5% (I)	11% (D)
1991	[6]	Y	Beam	-	Monotonic	(I)	-
1998	[13]	Y	B/C Assembly	7.27%- or 9.09%-drift	Cyclic	(U) - 32% (I)	28% (D) - 39% (I)
2001	[16]	Y	Bridge Column	3.125% drift	Cyclic	(U)	(D)
2002	[12]	Y	B/C Assembly	7.22% drift	Reverse Cyclic	(U) - 10% (I)	20% (D) - 5% (I)
2007	[17]	Y	Bridge Girder	15 to 20 mm mid-span displ.	Dynamic	(I)	(I)
2011	[20]	Y	Beam	-	Monotonic	(I)	-
2011	[22]	Y	Beam	-	Monotonic	21% (I)	(I)
2013	[18]	Y	H-Unit	Unknown - EQ	Cyclic	40% (I)	(U)
2018	[11]	Y	Beam	1.36% or 2.17% drift	Cyclic	4% - 7% (I)	12% - 21% (D)
1976	[9]	N	Masonry Components	-	Monotonic	(U) - Shear	-
1994	[23]	N	Brick Wall	10 - 20 mm horizontal displ.	Monotonic or Cyclic Shear	215% - 391% (I) - Shear	6% - 18% (I)
2001	[8]	N	Beam	-	Monotonic	15% (I)	-
2017	[24]	N	Beam	-	Monotonic	16% (D) - Flexure*	-

* Epoxy repair was completed using a gravity fed technique.

The table classifies results based on year and reinforcement and provides the post-repair results. (I) is an increase relative to the original, (D) is a decrease, and (U) unchanged.

Many factors influence the apparent effectiveness of epoxy resin repairs. Effectiveness was assessed by the percentage of stiffness reinstated and whether injected cracks remained closed. Additional factors to those mentioned earlier in this literature review include, failure mode (shear or flexure), quality of repair, experience and competency of contractors, epoxy to concrete or reinforcement bond (impacted by the epoxy resin product, and the presence of dust, moisture, or other foreign substances), and extent of damage to concrete, reinforcement, and bond. Specific factors for the tests summarized above, recognized by the report/article authors can be viewed in detail in the corresponding documents.

Appropriate engineering judgement should be utilized when developing a repair strategy, identifying the cause of cracks, likely extent of damage to the structure (with consideration not limited to residual crack width – consider damage to or extent of yielding of reinforcement), selection of the best product based on the crack location and size, selection of the optimum injection method, and selection of an experienced and competent contractor.

The author notes that axial load appears to have a relatively significant impact on the efficacy of epoxy repair. Results changed dramatically between the two examples; one where an applied axial load closed the cracks and the other where an applied axial load propped the cracks open. BMC consider that further testing is needed to evaluate the implications of applied axial load and its impacts on the efficacy of epoxy injection.

Conclusion

From the literature review conducted, BMC concludes that epoxy resin injection, when carried out using appropriate quality assurance measures, optimum method of placement, and an appropriate epoxy resin product, is an effective means of repairing reinforced and unreinforced concrete structural elements. Epoxy resin injection was found to reliably reinstate stiffness and durability. Strength and energy dissipation were largely not influenced by the repair because they are dependent on the condition of the reinforcement, which cannot be repaired through epoxy injection. Initial stiffness is important for SLS considerations/criteria; however, elements are required to be designed with a cracked section modulus since the adoption of NZS3101:1995. For ULS considerations, strength is more important. Also, the research reviewed indicated that after 3-4 cycles, the stiffness of the original specimen and the repaired specimen were approximately the same.

Further industry developments in the vacuum impregnation technique may be desirable chiefly when considering repair of beam-column joints or other applications where reinstatement of bond is very important or delamination is a significant risk. Epoxy resin injection is viable in wet or dry conditions, although special techniques are required for wet conditions. Additionally, research indicated that epoxy resin injection is still viable in variable/extreme environmental conditions, but requires fire protective coatings for applications where elements are designed for fire loads as epoxy resin loses strength rapidly at higher temperatures.

The author notes that although epoxy injection can reinstate bond between reinforcement and concrete, it cannot repair or in any other way alter the capacity of the reinforcement. As was indicated in the research reviewed, reinforcement can sustain a finite quantity of extreme loading cycles prior to fracture regardless of the quality or efficacy of the epoxy repair technique, thus the cause of cracking and extent of damage to the reinforcement should be thoroughly considered prior to the selection of a repair strategy. Similarly, the imperative for repair must also be considered, along with the required standard of repair pursuant to the applicable insurance response for earthquake damage. Epoxy repairs are not a universal cure that will deliver a step change in performance. In the appropriate situation and conditions however, the research detailed in this literature review demonstrates epoxy can provide good quality repairs.

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